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Distributed sensors with piezoelectric films in design of spatial filters for structural control

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Abstract

This paper discusses the spatial filtering in structural control by means of distributed PVDF films. A one-sided electrode with a honeycomb motif of variable porosity is used to tailor the effective piezoelectric properties of the film. The paper examines the design of the porous electrode for isotropic as well as orthotropic PVDF to achieve the desired spatial filtering properties, and validates the design with the manufacturing and testing of a volume displacement sensor. The technology for constructing transparent sensors is also examined.

1. Introduction

This paper is a follow-up to Ref. [1] which was motivated by the construction of spatial filters (within some frequency band) for various structural control applications. A review of the early work on spatial filters is available in Ref. [1] and is not duplicated here; additional key references on distributed PVDF sensors can be found in Ref. [2].

In the first part of Ref. [1], the construction of (reconfigurable) spatial filters with a regular array of discrete piezoelectric sensors connected to a linear combiner was addressed. The

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determination of the linear combiner coefficients was outlined both when a model of the structural system is available, and when experimental frequency response functions (FRFs) of individual sensors are available; their numerical calculation from noisy data was performed with a singular value decomposition, which eliminates the ill-conditioning of the rectangular matrix involved in the process. It was found that the construction of modal filters was possible within some frequency band, but the spatial filter departed from the ideal modal filter beyond some critical frequency due to spatial aliasing, which renders the sensor array sensitive to higher frequency modes, in addition to the targeted low-frequency one. The limit frequency above which the aliasing occurs is given by the natural frequency of the mode with wavenumber equal to the size of the sensor array. As an extension of modal filtering, the frequency shaping of open-loop FRF was also addressed, and it was illustrated by constructing a FRF with equal amplitude resonant peaks and alternating poles and zeros; this approach can be attractive for designing efficient active vibration control systems but, here again, aliasing occurs and reduces the roll-off of the open-loop transfer function at high frequency, bringing strong limitations on the controller bandwidth, as compared to the ideal filter.

The second part of Ref. [1] was devoted to a new type of distributed sensors aimed at overcoming the aliasing of discrete arrays; the distributed sensor was developed as a limit case of a discrete array filter when the number of elements of the array increases to infinity; unlike the approach based on tailoring the piezoelectric properties of the sensor, which is impossible to do at this time, this approach can be realized practically through the use of a one-sided porous electrode whose electrode density is adjusted to match the desired effective piezoelectric properties. For a very thin piezoelectric film (when the thickness is small compared to the size of the motif on the electrode), it has been shown by 3-D finite element calculations [4] that the relationship between the effective piezoelectric properties and the fraction of electrode area is almost linear; when the film thickness becomes comparable to the size of the motif of the electrode, tridimensional (edge) effects appear and the electric field lines are no longer normal to the electrodes, leading to nonlinearities in the relationship between the effective piezoelectric properties and the electrode porosity. The porous electrode concept was validated on various experiments such as: (i) modal filter of a cantilever beam [1,5], (ii) volume velocity sensor of a simply supported plate [5,6], and a transparent implementation of the volume velocity has been realized [6].

The purpose of this paper is to synthesize our most recent work on the construction of spatial distributed filters with PVDF films provided with a one-sided porous electrode. The paper is organized as follows: Section 2 recalls the various steps of the design of the porous electrode; Section 3 discusses the design of a volume displacement sensor for a simply supported rectangular plate and validates the design with an experiment where the output of the PVDF sensor is compared with that of a laser scanner vibrometer; Section 4 briefly reports on a transparent implementation and Section 5 compares the electrode design for orthotropic (uni-axial) and isotropic (copolymer) PVDF films.

2. Design of the porous electrode

The electrode design starts with a discrete array of large size which is used as a discretization of the distributed sensor. The linear combiner coefficients achieving the required spatial filtering properties are calculated according to the procedure described in Ref. [1]; this is illustrated in Fig. 1a. The polarization profile of the distributed spatial filter is then obtained by interpolating and smoothing the linear combiner coefficient diagram as in Fig. 1b; there is no obstacle in

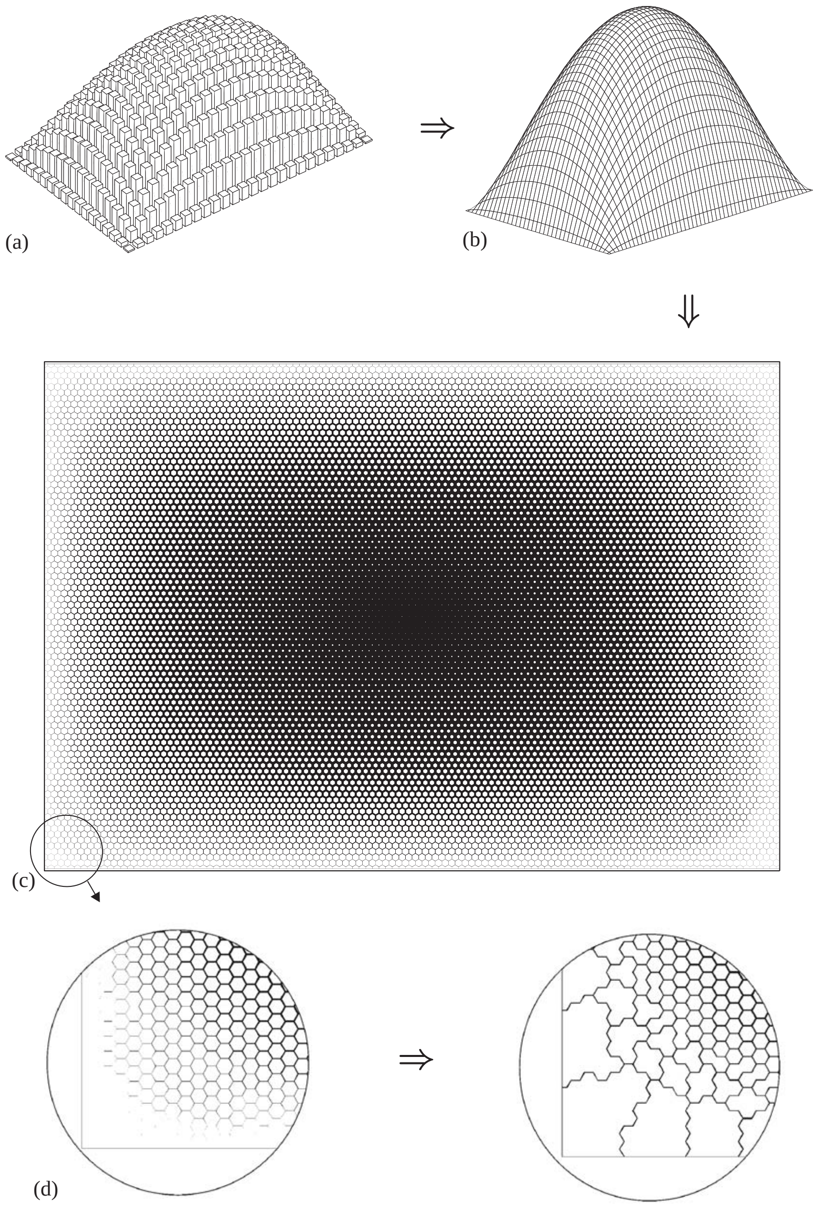

Fig. 1. Various steps of the design of the porous electrode: (a) computation of the weighting coefficients of the linear combiner, (b) smoothing of the coefficients to obtain the polarization profile, (c) transformation of the polarization profile into the fraction of electrode area leading to the honeycomb electrode profile, (d) redesign of the edge of the electrode to take care of the manufacturing tolerances and electrical connections.

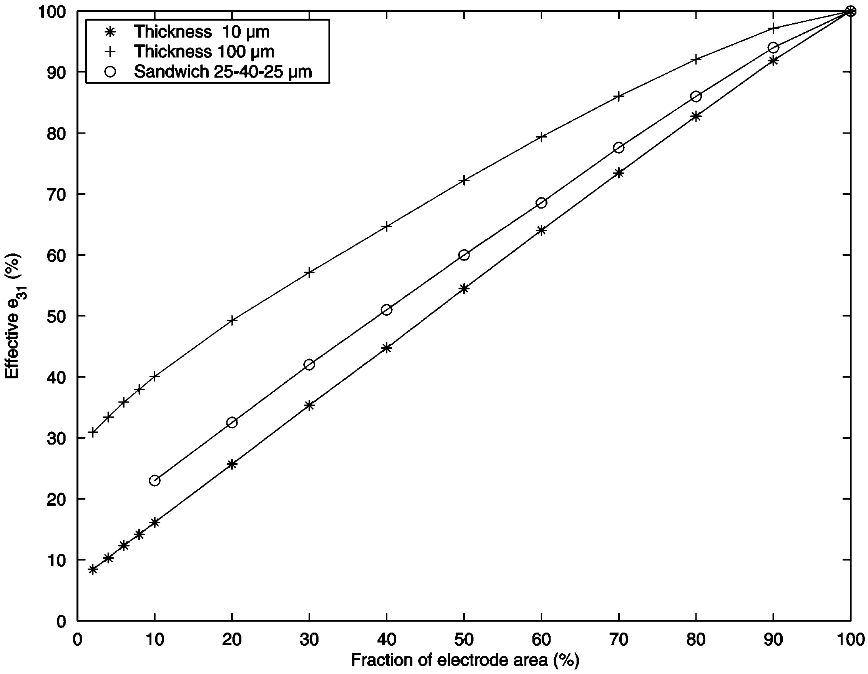

Fig. 2. Effective piezoelectric coefficient versus fraction of electrode area for an isotropic PVDF film of various thickness.

handling negative coefficients, by changing the polarity of the PVDF film. Next, the polarization profile can be converted into porosity profile of the honeycomb electrode (Fig. 1c) using the relationship between the effective piezoelectric properties and the fraction of electrode area (Fig. 2), obtained by homogenization from 3-D finite element calculations of the piezo film with appropriate electrical boundary conditions (potential difference $V = 0$ between the electrodes in this case). If the thickness of the film is small compared to the size of the motif, this relation can be assumed linear. The final step consists of adapting the edge of the electrode to take into account the technological constraints of the lithography process, in particular to keep the minimum thickness of the motif to a value compatible with manufacturing tolerances and to allow the electrical connection with the conditioning electronics (Fig. 1d).

3. Application

As an example of application, this section considers the design and construction of a volume displacement sensor of a baffled simply supported plate. The volume velocity of a vibrating plate is defined as

$$V = \int_S \dot{w}\, \mathrm{d}S, \tag{1}$$

where w is the transverse displacement of the plate and the integral extends over the entire plate area. It is a very important quantity in vibroacoustics, because it closely approximates the first radiation mode which is the dominant contributor to the sound power radiation at low frequency [7]. It is very tempting to try to develop a set of structural sensors measuring directly the volume velocity, or equivalently the volume displacement (by using a charge amplifier instead of a current amplifier). Elliott and co-workers [8] developed the so-called *quadratically weighted strain integrator sensor* (*QWSIS*) which consists of slicing the electrode into narrow strips with parabolic shape. The sensor is based on the assumption that the volume displacement of each strip can be calculated according to the beam theory. This sensor is biased because strictly unidirectional PVDF does not exist (the piezoelectric constant e_{32} is always at least 10% of e_{31}) and it is prone to spatial aliasing due to the finite number of strips. Our research group pursued an alternative strategy based on discrete array sensors which were simpler and reconfigurable [9]; it worked well at low frequency (below 250 Hz) where the sensor is really useful, but the sensor output was much degraded at higher frequency because of aliasing, which made it difficult to integrate in a control system [3]. This failure to build a discrete array volume displacement sensor with adequate roll-off at high frequency was the origin of the present work.

In this study, we have designed, built and tested a volume displacement sensor with the porous electrode technology. The test article is shown in Fig. 3; it consists of a 180 mm × 260 mm × 1.6 mm glass epoxy (PCB) board with a 37 μm thick copper electrode. The electrode is full at the center of the plate and a honeycomb motif with variable width appears when one moves toward the edges; the honeycomb motif is etched with standard PCB technology in the copper electrode and a 40 μm thick PVDF copolymer film with a one-sided continuous electrode is glued on top of it to form the distributed sensor with variable effective piezoelectric properties. Accurate etching of a PCB copper electrode is technologically much simpler than the silver electrode of a PVDF film as used in the validation test on a beam in Ref. [1], and it is possible to

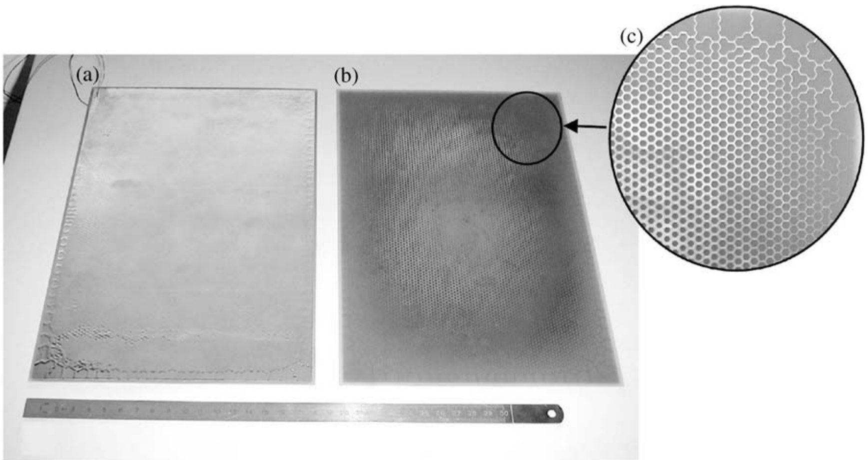

Fig. 3. (a) Top view of the PVDF film mounted on the plate, (b) PCB plate without PVDF film, showing the honeycomb etched in the copper electrode, (c) detail of the honeycomb electrode with variable porosity.

achieve a better resolution here (better than 100 μm, instead of 500 μm with silver electrodes on PVDF).

The design of the electrode was done with an analytical model of the simply supported plate, using analytical mode shapes and neglecting the membrane strains in the strain-induced piezoelectric charges [3]; if necessary (especially for more complicated boundary conditions), finite element simulations could also be used at this stage [4], but the analytical model turned out to be sufficient in this case.

The procedure for determining the linear combiner coefficients α_i is the following (Fig. 4): a disturbance is applied to the baffled plate (e.g. uniform pressure) and the analytical FRF of the volume displacement $V(\omega)$, and the electric charges on individual sensors $Q_i(\omega)$ are computed. Since the requested output of the linear combiner is the volume displacement, we must have

$$V(\omega) = \sum_{i=1}^{n} \alpha_i Q_i(\omega). \tag{2}$$

Writing this equation for a set of l discrete frequencies ($l > n$) regularly distributed over the frequency band, we get a redundant system of equations

$$\begin{pmatrix} Q_1(\omega_1) & \dots & Q_n(\omega_1) \\ Q_1(\omega_2) & \dots & Q_n(\omega_2) \\ & \dots & \\ Q_1(\omega_l) & \dots & Q_n(\omega_l) \end{pmatrix} \begin{pmatrix} \alpha_1 \\ \alpha_2 \\ \dots \\ \alpha_n \end{pmatrix} = \begin{pmatrix} V(\omega_1) \\ V(\omega_2) \\ \dots \\ V(\omega_l) \end{pmatrix} \tag{3}$$

or, in matrix form

$$\mathbf{Q}\alpha = \mathbf{V}. \tag{4}$$

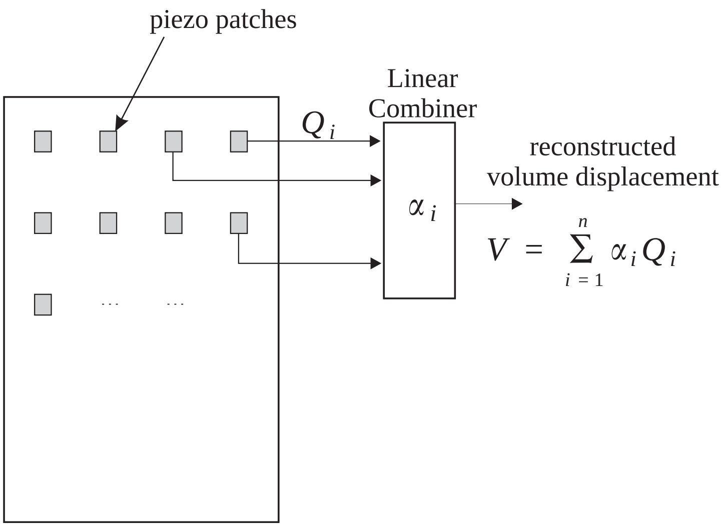

Fig. 4. Principle of the discrete array sensor.

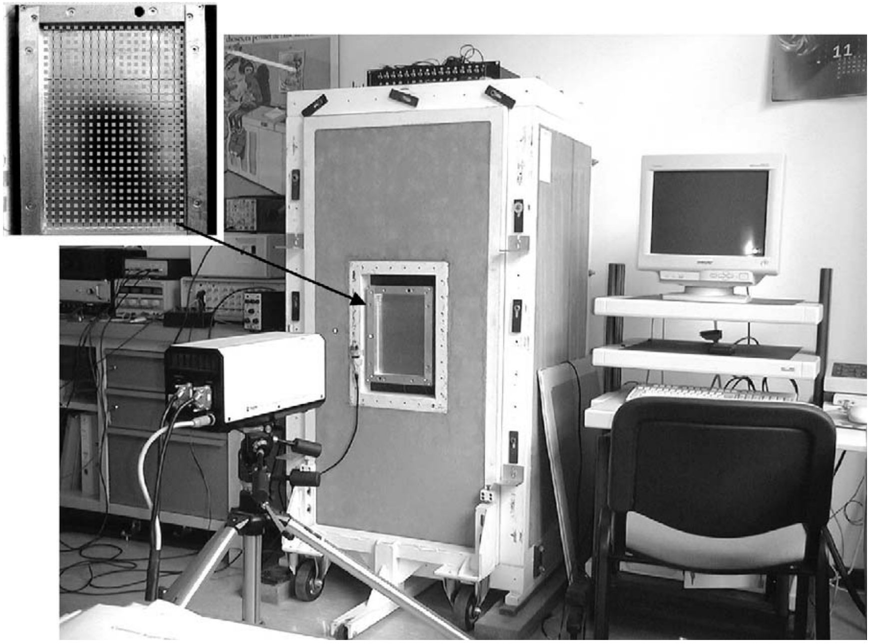

Fig. 5. Experimental set-up used to test the volume displacement sensor and (upper left) measurement mesh used for the laser vibrometer.

This redundant system of equations is then solved with a singular value decomposition [9,3], leading to the weight distribution of Fig. 1a. The other steps of the design follow Fig. 1; for the very thin electrode used in this experiment (40 μm), it was sufficient to assume a linear relation between the effective piezoelectric properties and the fraction of electrode area.

Fig. 5 shows the experimental set-up to assess the quality of the sensor; the plate is first placed in an aluminum frame with an elastomer joint, to approximate simply supported boundary conditions; the aluminum frame is mounted in the opening of a concrete acoustic chamber with a loudspeaker inside. The volume displacement is measured with a scanner laser vibrometer (the mesh used in the laser measurement is also shown in Fig. 5).

Fig. 6 compares the FRF between the current applied to the loudspeaker and the volume displacement sensed with (i) the PVDF sensor with porous electrode and (ii) the laser vibrometer; both the amplitude and phase diagrams match well.

Fig. 7 shows the same comparison for a point force applied with a voice coil acting near a corner, at 35 mm from the edge of the plate. The agreement between the curves is still good, although larger differences are observed; part of these are due to the fact that the coil adds a discrete mass of 1 g near the corner of the plate, altering its mode shapes (in particular some anti-symmetric modes which did not contribute to the volume displacement for the original plate). Thus, the porous sensor which was designed for producing the volume displacement of a

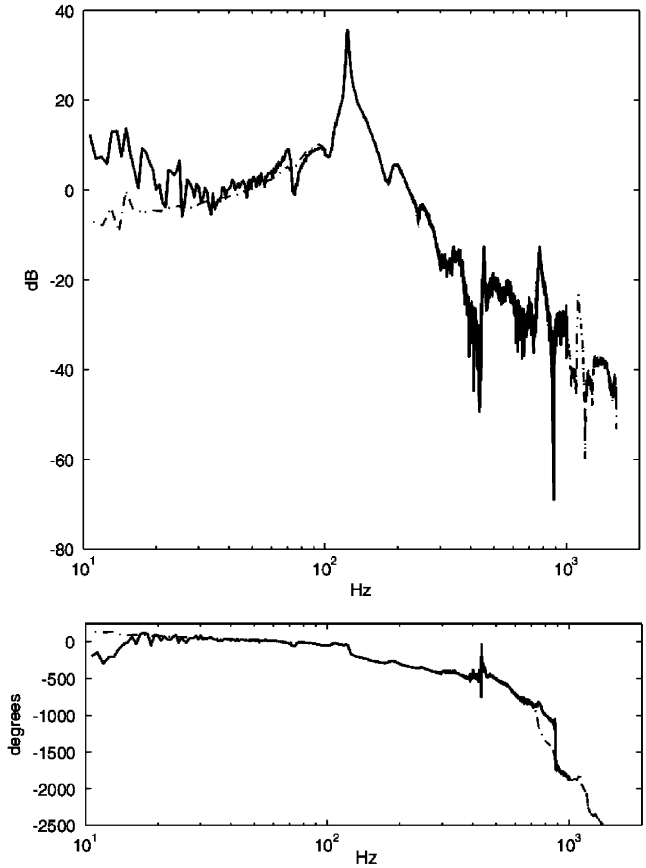

Fig. 6. Glass-epoxy plate. FRF between the current applied to the loudspeaker and the volume displacement; comparison between the porous piezoelectric sensor (dotted line) and the laser vibrometer (full line).

symmetric plate is no longer totally appropriate. Overall, the quality of the volume displacement sensor looks quite good.

4. Transparent implementation

Transparent sound radiation sensors could open the way to new applications such as active windows. Fig. 8 shows a transparent implementation of the volume displacement sensor. It consists of a 40 μm PVDF film glued on a glass plate with 25 μm connecting layers. The transparent electrodes are made of indium tin oxide (ITO). A laser lithography process is used to shape the electrode. The test article has the same size (180 mm × 260 mm) as the glass-epoxy plate tested above and it has been tested with the same set-up of Fig. 5. Fig. 9 shows a comparison of the FRF between the loudspeaker input and the sensor output obtained, respectively, with the

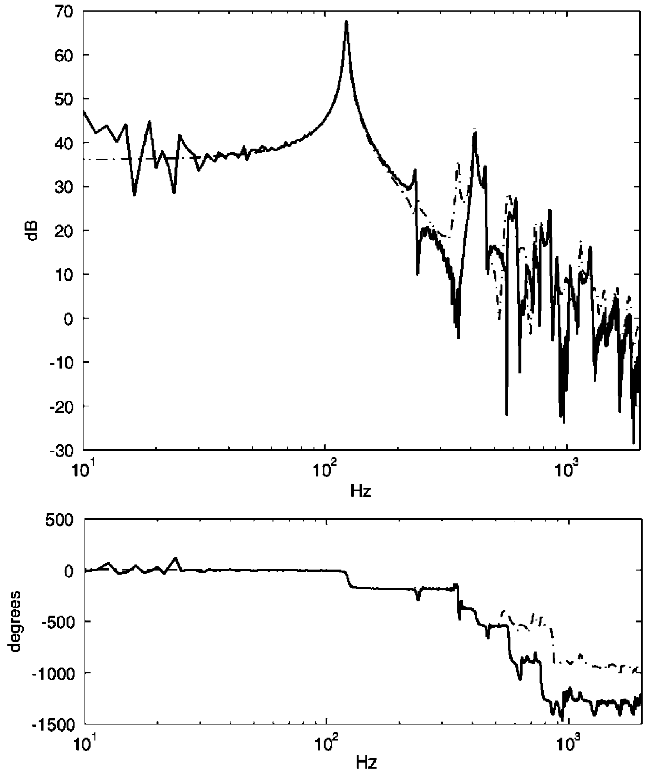

Fig. 7. Glass-epoxy plate. FRF between a point force excitation near a corner of the plate and the volume displacement; comparison between the porous piezoelectric sensor (dotted line) and the laser vibrometer (full line).

transparent sensor and the laser vibrometer. Once again, the agreement between the FRFs is excellent.

5. Orthotropic PVDF sensor

The results of Fig. 10 have been obtained with isotropic copolymer exhibiting isotropic piezoelectric properties ($d_{31} = d_{32} = 2.5\,\mathrm{pC/N}$). Uni-axial PVDF has several advantages over copolymer: it is more sensitive, is a lot cheaper and can be more easily mass produced. An alternative sensor has been designed and manufactured with uni-axial PVDF with the following properties: $d_{31} = 22.5\,\mathrm{pC/N}$, $d_{32} = 2.5\,\mathrm{pC/N}$. The design follows the same lines as before, except that the orthotropy of the sensor must be included in the model, affecting the FRF expression of the electric charge Q_i. Everything else is the same. Fig. 10 compares the piezoelectricity profile of the sensor in the two cases tested; note that the overall sensitivity of the anisotropic sensor is much higher because of the much larger value of d_{31}. The quality of the isotropic sensor has been found to be very similar to that of the copolymer one.

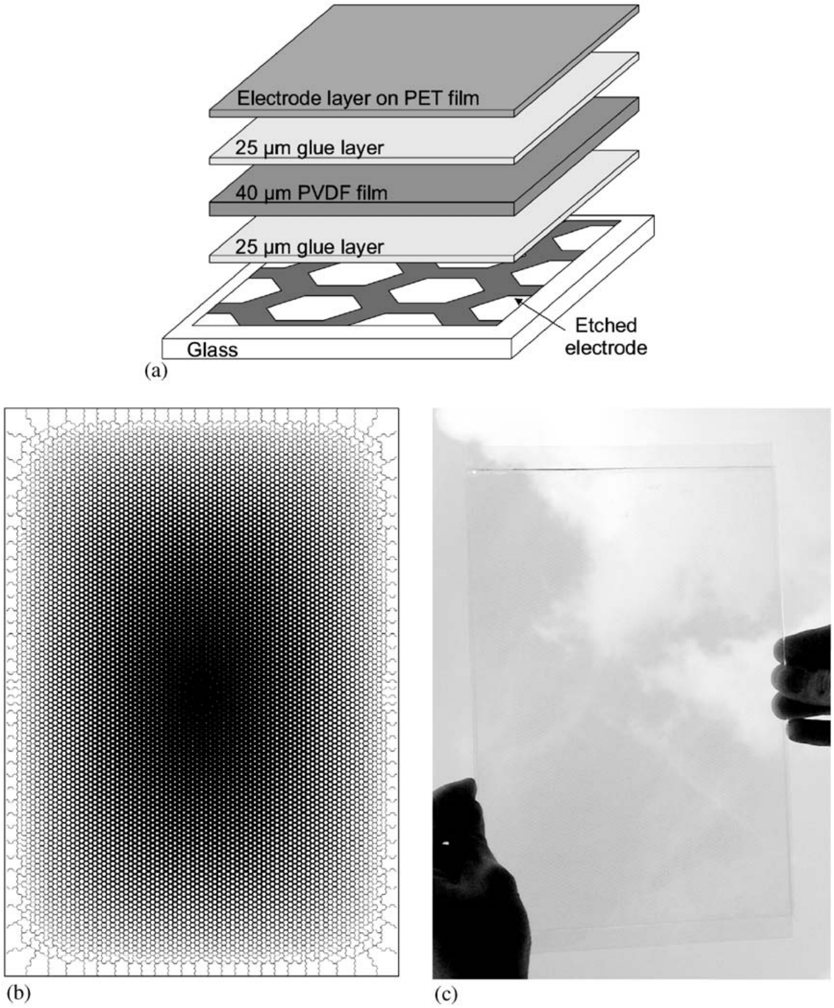

Fig. 8. Transparent PVDF sensor tailored for measuring the volume displacement: (a) detail design, (b) electrode profile, (c) sensor mounted on a glass plate.

6. Conclusion

This paper has addressed the design and manufacturing of distributed sensors from PVDF films. A concept of honeycomb porous electrode has been used to tailor the effective piezoelectric properties in two dimensions. The methodology for tailoring the porosity of the electrode has been reviewed and illustrated with an application to the design of a volume displacement sensor; the technique has been validated with various experiments including a glass-epoxy plate with copolymer sensor, a glass plate with copolymer sensor and a glass plate with uni-axial PVDF. The technology of manufacturing transparent electrodes has also been tested successfully.

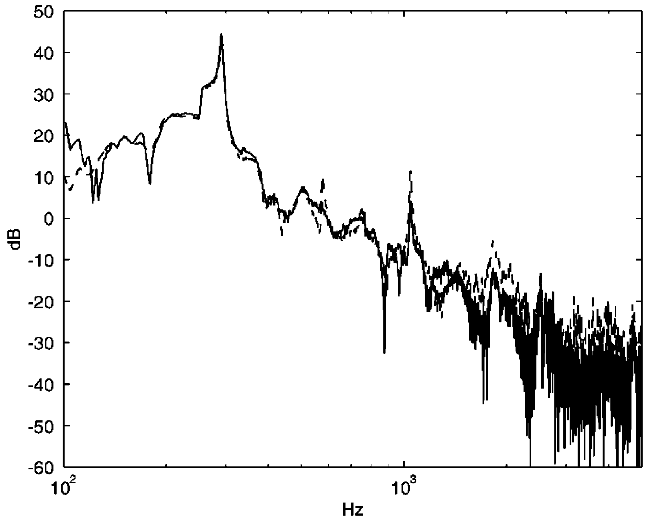

Fig. 9. Transparent (copolymer) PVDF sensor mounted on a glass plate. FRF between the current applied to the loudspeaker and the volume displacement; comparison between the porous piezoelectric sensor (dotted line) and the laser vibrometer (full line).

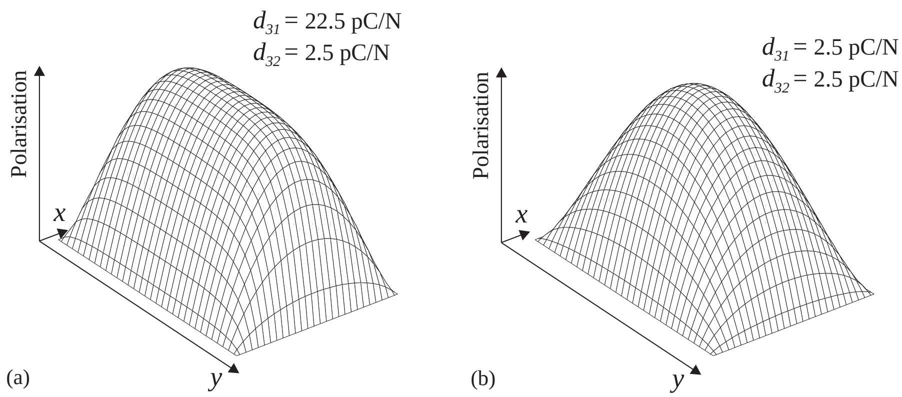

Fig. 10. Comparison of the polarization profile of the volume displacement sensor for various piezoelectric properties: (a) uni-axial PVDF, (b) isotropic PVDF (copolymer).

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