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RESEARCH ARTICLE

Study of Pressure-Sensitive Materials for Floor Sensor Networks

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Abstract

This paper presents a comparative study of pressure-sensitive sensor materials being suitable for monitoring purposes in pressure mapping sensor networks. Four sensor materials working on piezoresistive, piezoelectric, quasi-piezoelectric and capacitive principle have been discussed including the built-up, the working principle, the manufacturing and the most important properties. Additionally, the electromechanical models of the sensor elements have been introduced and verified by comparing the modelled and measured sensor characteristics. The studied materials were compared and evaluated using a decision matrix with respect to the applicability as a thin and flexible pressure sensor unit in a competitive large-area floor sensor network.

Keywords

surveillance monitoring, pressure measurement, piezoresistive films, piezoelectric films, ferroelectret films, dielectric films

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1 Introduction

A pressure mapping system is an array of sensors being arranged in a two-dimensional pattern (usually in matrix structure) that measures interface pressure, which is defined as the pressure that occurs at the interface between the body and the support surface.

Pressure mapping is an innovative technology providing a solution for a wide range of applications that has been available for many years but is still not widespread owing to the high prices of the used sensor materials. Nowadays, pressure mapping systems are used mainly by product designers and test engineers throughout the research, design, testing, and manufacturing cycle to verify and enhance product performance. Such systems are also used in medical research to study the pressure distribution on the surface of the human body (e.g.: in-shoe pressure analysis). Some medical studies and applications using this technology are presented in [2].

The main objective of the presented study was to find a suitable pressure-sensitive sensor material for a competitive and universal floor sensor network [7], which provides a platform technology for a wide range of medical, home automation and security applications. In health care, such sensor systems can detect patients leaving their beds or their rooms and transmit alarm signals through indoor call systems or radio components. Floor sensor systems provide a variety of applications in the fields of home automation and security as well. Switching of orientation lights, controlling of automatic doors, fall detection, burglar alarm, activity monitoring as well as presence-controlled light and temperature management are just a few of the many possible applications.

2 Sensor materials

Pressure mapping systems are highly dependent on the material properties of the pressure transducer. The most important properties of a sensor element are the scalability (which allows fitting the geometrical resolution according to the application specific requirements), the sensor linearity (which allows a weight measurement independent from the pressure distribution on the elements) and the sensor respectively noise sensitivity (which allows a suitable measuring precision). The specific cost of the sensor material, the manufacturing costs of the sensor matrix respectively the necessary evaluation electronics and the patent situation are also important in order to provide a competitive technology.

Based on a systematic literature research on the available pressure-sensitive materials, four sensor films have been considered for further analysis including a piezoresistive sensor material (Zoflex® Pressure-Activated Conductive Rubber Sheet from RF Microlink [9]), a piezoelectric sensor material (Metallized Piezo Film Sheet from Measurement Specialities Inc. [3]), a ferroelectret sensor material (Emfit L-Series Sensor from Emfit Ltd. [4]) and an electro-active polymer sensor material (Polypower® DEAP Film from Danfoss Polypower A/S [5]).

2.1 Piezoresistive sensor film

Of particular interest for pressure-sensing purposes are piezoresistive sensors. Most of the reported pressure-mapping arrays are consisting of such sensor elements. They utilize the effect that the resistivity of some particular materials is altering by applying mechanical stress on its surfaces.

A common group of piezoresistive materials are materials consisting of both electrically conducting and non-conducting particles suspended in matrix. These materials are normally supplied as a polymer sheet or ink that can be applied by screen printing. The particles are sub-micrometer sizes and are formulated to reduce the temperature dependence as well as to improve the mechanical properties and to increase the surface durability. Applying a force to the surface of the sensing film causes particles to touch the conducting electrodes as well as each other resulting in a decreasing electrical resistance of the film. Such sensor build-up and its simplified electrical model are shown in Fig. 1.

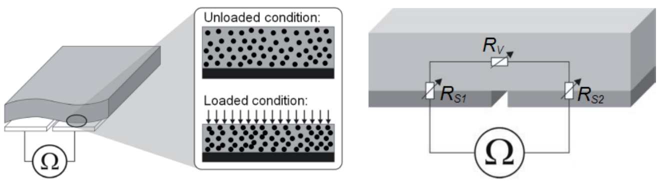

Fig. 1 Working principle of a piezoresistive pressure sensor [11]

The resistance of the sensor film can be modelled by three single resistors. R_V represents the volume resistivity of the sensor material between the electrodes while R_{S1} and R_{S2} are the surface resistivity. Both volume and surface resistivity are varying with the applied load.

Another working principle is illustrated on Fig. 2. This solution utilizes a conductive polymer material having a rough surface between the electrodes and itself [8]. If a load is applied to the sensor cell, the rough surface of the sensor material is pressed onto the electrode's surface. This compression results in incrementing the contacting area, leading to a decreased electrical interface resistance between the sensor material and the electrode. The volume resistivity (R_V) of the sensor material can be assumed to be constant while the surface resistivity (R_{S1} and R_{S2}) is varying with the applied load.

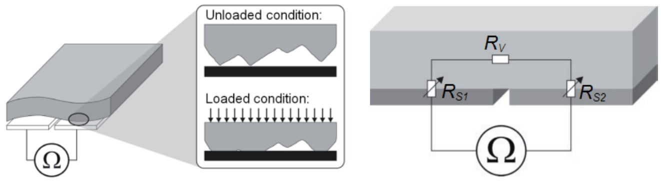

Fig. 2 Working principle of a piezoresistive pressure sensor [8]

Both kind of sensor material show a hyperbolic style characteristic [11] between the applied load and the electrical resistance. This nonlinear behaviour is of special interest e.g. in collision detection, since for lightweight contacts to its surface the sensor is more sensitive than at high loads, consequently the measurement range is expanded. However, in case of floor sensor applications, the strongly non-linear sensor characteristic is a significant disadvantage. With sensor elements having a non-linear behaviour, a force or weight measurement can only be performed in case of a uniform pressure distribution. A uniform pressure distribution over the sensor elements can only be assumed if the sensor elements are significantly smaller than the contact surface which strongly limits the scalability. Additionally, owing to the inhomogeneous structure and the manufacturing tolerances, the typical accuracy without additional calibration is low (measurement results may differ 10% and more).

Piezoresistive pressure sensors are in general very robust on overpressure, shock and vibration due to its simple construction but they can be damaged if pressure is applied for a longer time period (hours).

As with all resistive based sensors, pressure-sensing resistors require a relatively simple interface, however the sensor material self is very expensive for a large surface application (the price of such sensor films is about 880 €/m^2 according to the prices of the company RF Microlink).

2.2 Piezoelectric sensor film

Piezoelectric pressure sensors are using the piezoelectric effect to measure changes in the pressure being applied on its surfaces by converting the mechanical stress to an electrical charge. Many materials, including natural and synthetic materials as well, exhibit piezoelectricity. The most commonly used materials are crystals (e.g.: quartz), ceramic materials (e.g.: lead zirconate titanate) and particular polymers (e.g.: polyvinylidine fluoride).

Polyvinylidine fluoride (PVDF) is a thermoplastic flour polymer that can be manufactured as a thin and flexible foil material. Ceramic materials are made piezoelectric by applying a very high polarizing voltage during its manufacturing. This technique has been found to work effectively on PVDF as well.

The polarization occurs above the Curie temperature, which is slightly below the melting point. The high poling voltage polarizes and aligns the dipole molecules while the PVDF material is stretched as shown in Fig. 3. The cooling down of the material is performed still in the polarizing voltage, whereby the molecules are staying polarized.

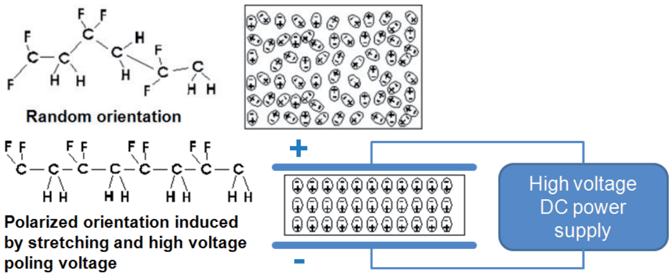

Fig. 3 Build-up and manufacturing of polarized PVDF polymer [3]

Unlike ceramics, where the piezoelectric effect arises from the asymmetrical crystal structure of the material, in PVDF material, the molecular alignment of the material induces it. When a mechanical load is applied in the direction of the polarisation, the distance between the molecular chains decreases primarily owing to the relatively weak van der Waals and electrostatic interactions between chains in comparison to the strong covalent bonds within the chain. The decreasing distances of the molecule chains result in an increase of the dipole density and thus in an increase of the charges on the electrodes, yielding a negative d_{33} piezoelectric coefficient.

The PVDF sensor film is a relatively new class of piezoelectric sensors. The PVDF sensor film is a thin PVDF sheet that has a thin electrically conductive material (e.g.: silver, nickel-copper alloy) deposited on each side allowing to measure the changes in the surface charge density. Such PVDF films exhibit piezoelectricity several times greater than quartz.

Beside the excellent piezoelectric properties, PVDF is also pyroelectric, producing electrical charge in response to a change in temperature. PVDF strongly absorbs infrared energy in the 7-20µm wavelengths, covering the same wavelength spectrum as heat from the human body.

Linear electro-elastic constitutive equations are commonly used to describe the coupling of dielectric, elastic, and piezoelectric properties in piezoelectric materials [13]:

$$\begin{bmatrix} \hat{S} \\ \hat{D} \end{bmatrix} = \begin{bmatrix} \hat{s} & \hat{d}^T \\ \hat{d} & \hat{\varepsilon} \end{bmatrix} \begin{bmatrix} \hat{T} \\ \hat{E} \end{bmatrix} \tag{1}$$

where

$\hat{S}$ – 6x1 column vector of strain

$\hat{T}$ – 6x1 column vector of stress

$\hat{D}$ – 3x1 column vector of electric displacement

$\hat{E}$ – 3x1 column vector of electric field

$\hat{s}$ – 6x6 compliance matrix

$\hat{\varepsilon}$ – 3x3 permittivity matrix

$\hat{d}$ – 3x6 piezoelectric matrix

In sensor applications, the PVDF behaviour is usefully described by the second row of constitutive equations:

$$\begin{bmatrix} D_1 \\ D_2 \\ D_3 \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 & 0 & d_{15} & 0 \\ 0 & 0 & 0 & d_{24} & 0 & 0 \\ d_{31} & d_{32} & d_{33} & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} T_{11} \\ T_{22} \\ T_{33} \\ T_{23} \\ T_{13} \\ T_{12} \end{bmatrix} + \begin{bmatrix} \varepsilon_{11} & 0 & 0 \\ 0 & \varepsilon_{22} & 0 \\ 0 & 0 & \varepsilon_{33} \end{bmatrix} \begin{bmatrix} E_1 \\ E_2 \\ E_3 \end{bmatrix} \tag{2}$$

The structures of the piezoelectric and the permittivity matrices are due to the reported material symmetry (transversely isotropic material). The stress vector being expressed in Voigt notation represents the independent elements of the symmetric Cauchy stress tensor. The first index of its components indicates the normal of the plane on which the stress acts and the second index denotes the direction in which the stress acts. Axis 3 is assigned to the direction of the polarization while axes 1 and 2 lie in the plane of the sensor film perpendicular to axis 3. As the charge signal is measured with a charge amplifier (Fig. 4), which converts the charge input into a voltage without supplying any electric field between its input terminals (owing to the virtual ground at the inverting input), the electric field can be neglected.

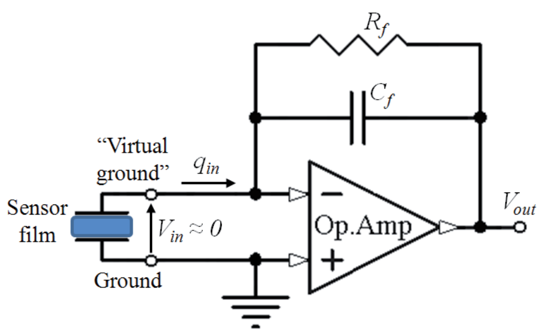

Fig. 4 Simplified electrical model of charge amplifier

Therefore, when the film is used in thickness mode (mechanical stress is applied in the 3-direction), the previous set of equations reduces to:

$$D_3 = d_{33} T_{33} \tag{3}$$

The charge generated by the PVDF sensor can be obtained by integrating the electrical displacement D_3 over the loading area A_c:

$$q = \iint_{A_C} D_3 dA = d_{33} T_{33} A_C = d_{33} F \tag{4}$$

The piezoelectric coefficient of the material (d_{33}) is given from the product specification of the sensor film. According to the electromechanical model (4), the sensor film exhibits an excellent linear characteristic between the applied load and the generated charge fulfilling one of the most important requirements for floor sensor application, however the strong pyroelectrical behaviour is a significant disadvantage as the effect of heat transfer and radiation can be considered as disturbances in pure pressure-sensing applications and therefore additional measures are necessary to reduce or eliminate these influences.

Due to the excellent sensor sensitivity and simple measuring principle, PVDF sensors require a simple measuring electronics. However, owing to the high prices of the raw material and especially the very costly manufacturing process, the sensor material is extremely expensive for a large surface application (the price of the sensor film is about 2150 €/m^2 according to the prices of the company Measurement Specialities Inc.).

2.3 Ferroelectret sensor film

Ferroelectrets (also known as piezoelectrets) are usually polymer materials consisting of a cellular structure filled with air voids, wherein permanent electric charges are stored.

Similarly to piezoelectric films, these materials convert mechanical stress into proportionate electrical energy and conversely, it mechanically expands when voltages of opposite polarities are applied. Ferroelectrets are also pyroelectric, converting heat into electrical charge but with much less intensity than the piezoelectric PVDF film. Most commercially produced ferroelectret sensors are based on synthetic polymers as fluoropolymers (e.g. PVTF or PVDF), polypropylene (PP) or polyethyleneterephthalate (PET) rolled to thin films. For low cost solutions, polypropylene is used which is more competitive but has relatively low temperature stability.

The PP based ferroelectret film is manufactured in several steps [15]. In a first step, air voids are generated in a composite film consisting of polypropylene and microparticles by biaxial stretching. The size of the generated air voids are increased through applied air pressure and heating cycles. The resultant cellular PP has lenticular shaped voids being capable of storing large permanent charge as shown in Fig. 5.

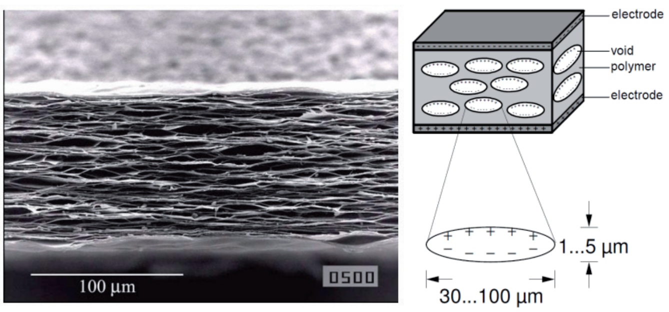

Fig. 5 Build-up of cellular PP film [14]

The charge is injected into the air voids through electrode or corona poling. The electric charge within an electret decays exponentially. The decay constant is a function of the relative dielectric constant of the material and its bulk resistivity. Materials with extremely high resistivity such as PP may retain excess charge for many hundreds of years [16].

In contrast to the piezoelectric PVDF material, where the electric polarisation is arising from molecular dipole moments, the polarisation of ferroelectrets is due to the macroscopic dipole moments of the charged air voids resulting in a quasi-piezoelectric behaviour of the material. An applied mechanical stress in the 3-direction decreases the thickness of the film. The thickness decrease occurs dominantly across the voids, the macroscopic dipole moments decrease and so do the surface charge density, yielding a positive d_{33} (quasi-piezoelectricity).

Sessler and Hillenbrand [17] proposed the electromechanical model of such cellular electrets films. The charged cellular material is assumed to consist of a layered structure with electrodes on top and bottom as shown in Fig. 6.

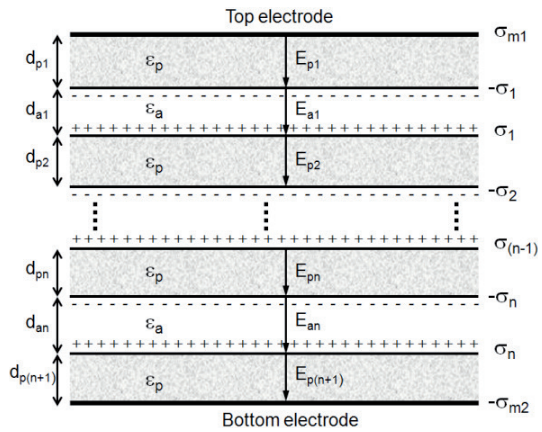

Fig. 6 Simplified model of cellular PP film [17]

The structure comprises solid and air layers of thicknesses d_{pj}, and d_{ai}, respectively with j=1, 2, .., n+1 and i=1, 2, .., n, where n is the total number of air voids. The layers are assumed to be laterally uniform. It is further assumed that the two solid surfaces confining the i-th air layer carry a total planar charge density of σ_i, and $-\sigma_i$ respectively and that no volume charges exists. The quantity σ_i, includes all permanent charges. The permanent charges on the two sides of the air gap are taken to be equal in magnitude since it is assumed that they originate from discharges in the air gap during poling. Figure 6 also shows the denomination of the electric fields E_{pj}, and E_{ai} in the solid and air layers. The electric fields can be expressed using Gauss's and Kirchhoff's laws. For the solid-air interfaces confining the i-th air void, Gauss's law can be written as:

$$-\varepsilon_p E_{pi} + E_{ai} = -\sigma_i / \varepsilon_0 \tag{5}$$

$$\varepsilon_p E_{p(i+1)} - E_{ai} = \sigma_i / \varepsilon_0 \tag{6}$$

Substituting (5) into (6), the relation between the electric fields of the polypropylene layers can be expressed as:

$$E_{p1} = E_{p2} = E_{p3} = ... = E_{p(n+1)} = E_p \tag{7}$$

The total electric potential between the electrodes can be written for short-circuit condition from Kirchhoff's second law:

$$\sum_{j=1}^{n+1} d_{pj} E_{pj} + \sum_{i=1}^{n} d_{ai} E_{ai} = 0 \tag{8}$$

Using the Equations (5), (7) and (8), the electric field inside the polypropylene layers can be expressed as:

$$E_p = \frac{\sum_{i=1}^{n} d_{ai}\sigma_i}{\varepsilon_0 \left(d_p + \varepsilon_p d_a\right)} \tag{9}$$

where
d_p – total thickness of polypropylene layers
d_a – total thickness of air layers

The charge on the top electrode is given by:

$$\sigma_m = \varepsilon_0 \varepsilon_p E_p = \frac{\varepsilon_p \sum_{i=1}^{n} d_{ai}\sigma_i}{\left(d_p + \varepsilon_p d_a\right)} \tag{10}$$

The surface charge depends on the thickness change of the film caused by an applied force. If the polypropylene layers are considered to be stiff enough to maintain their thickness, the thickness variation (Δd) can be considered to be compression of the air voids (Δd_a) only and the strain relation can be rewritten as:

$$\frac{\Delta d}{d} = \frac{\Delta d_a}{d} = \frac{p}{Y} \tag{11}$$

where
d – total thickness of sensor film
Y – Young's modulus
p – applied pressure on sensor film

After differentiating σ_m in respect with d_a one gets:

$$\frac{\partial \sigma_m}{\partial d_a} == \varepsilon_p \frac{d_p \sum_{i=1}^{n} d_{ai}\sigma_i}{d_a \left(d_p + \varepsilon_p d_a\right)^2} \tag{12}$$

Using the strain relation (11) one gets the sensor sensitivity from (12) in finite-difference form as:

$$\frac{q}{F} = \frac{\Delta \sigma_m}{p} = \frac{\varepsilon_p d}{Y} \frac{d_p \sum_{i}^{n} d_{ai}\sigma_i}{d_a \left(d_p + \varepsilon_p d_a\right)^2} \tag{13}$$

From (13), ε_p and Y are known material constants, d is known and d_p and d_a can be determined from the densities. The remaining quantities σ_i and d_{ai} have to be estimated based on the parameters of the poling process and on micro-photographs of the cross section of the film. According to the comparison of the theory with experimental results in [17], the above model for the pseudo-piezoelectric behaviour of the cellular material is based on reasonable assumptions indicating a linear characteristic between the applied load and the generated charge. However, the characterisation of the material was performed only by applying mechanical load at small contact area (1mm^2), where the assumption of material homogeneity may be more applicable.

Due to the good sensor sensitivity and simple measuring principle, cellular PP sensor films require a simple measuring electronics. However, owing to the high prices of the raw material and especially the costly manufacturing process, the sensor material is very expensive for a large surface application (the price of the sensor film is about 1100 €/m^2 according to the prices of the company Emfit Ltd.).

2.4 Electro-active polymer sensor film

A dielectric electro-active polymer (DEAP) is an elastomeric polymer sheet or silicon film coated on both sides with conductive material acting as electrodes. A sheet of the material is equivalent to a parallel plate capacitor and its capacitance is dependent on the area of the electrodes and the distance between them. These geometries are altered by applying mechanical stress on the sheet resulting in a changing capacitance, thus such films can be used as a capacitive displacement or pressure sensor.

Danfoss PolyPower A/S develops and manufactures a special optimized DEAP material [5]. The PolyPower DEAP film consists of a thin silicone dielectric material (~40µm) with a special corrugated surface (~7µm) and very thin layer of compliant metal electrodes (~100nm) on top of it. During the roll-to-roll manufacturing, two sheets of on one side corrugated and metallised silicon films are laminated together resulting in the patented design as can be seen in Fig. 7, which ensures significantly higher performance for both sensor and actuator applications than other alternative design of DEAP materials.

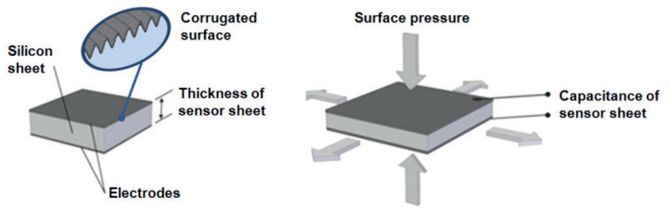

Fig. 7 Polypower DEAP [5]

Using the perturbation theory, the axisymmetric indentation of a compressible elastic thin film bonded to a rigid substrate was analyzed by Yang [19] for a contact radius much larger than the thickness of the thin film. As result of the analysis, an explicit expression for the relation between indentation load and indentation depth has been derived:

$$F = \frac{\left(1-\nu\right) A_c Y}{\left(1+\nu\right)\left(1-2\nu\right) d_0} \delta \tag{14}$$

where
ν – Poisson's ratio
A_c – loading area

Y – Young's modulus
d_0 – thickness of unloaded sensor sheet
δ – indentation depth

Considering the DEAP film as a parallel-plate capacitor, the capacitance of the film under the loaded area can be expressed as:

$$C = \varepsilon_r \varepsilon_0 \frac{A_c}{d} = \varepsilon_r \varepsilon_0 \frac{A_c}{d_0 - \delta} \tag{15}$$

Using (15) the capacitance change in respect of the thickness change can be described as:

$$\Delta C = C_1 - C_0 = \varepsilon_r \varepsilon_0 \frac{A_c}{d_0 - \delta} - \varepsilon_r \varepsilon_0 \frac{A_c}{d_0} \tag{16}$$

Substituting (14) into (16) one obtains:

$$\Delta C = \varepsilon_r \varepsilon_0 \frac{A_c}{d_0} \frac{F}{\dfrac{(1-\nu) A_c Y}{(1+\nu)(1-2\nu)} - F} \tag{17}$$

All parameters of the electromechanical model are given from the product specification of the sensor film. The electromechanical model (17) of the sensor film indices a non-linear characteristic between the applied load and the capacitance change of the sensor film, however the expected linearity error is low in the desired load range.

Due to the low sensor sensitivity, in comparison to the piezoresistive, piezoelectric and ferroelectret materials much more complex evaluation electronics is necessary. The most common way to measure small capacitance changes of a sensor is using active bridge circuits [6] applying compensation techniques to cancel the effect of the environmental interference, the in-circuit noise, the propagation delay of the measuring signal and the parasitic elements.

The price of the sensor material is moderate in contrast to the previously discussed sensor materials (the price of the sensor film is about 335 €/m^2 according to the prices of the company Danfoss Polypower A/S). Furthermore, the applied scalable roll-to-roll manufacturing technology [20] and the lower raw material costs allow a significant decrease of specific costs in case of larger production volumes.

3 Characterisation

In case of the studied piezoresistive materials, the sensor linearity was investigated and well documented by the manufacturers reporting a non-linear behaviour in all cases [8-10]. Typical sensor characteristics for three different flat-ended cylindrical indenters having a diameter of 40, 55 respectively 70 mm are shown in Fig. 8.

On the contrary, regarding the studied piezoelectric, ferroelectret, and electro-active polymer sensor materials no credible specification of the sensor linearity have been found, however, the sensor sensitivities are given as a constant suggesting a linear behaviour. To verify the sensor linearity and the presented electromechanical models, a characterisation was performed on these sensor materials. The measurement set-up being used for the characterisation of the piezoelectric (PVDF) and the ferroelectret (cellular PP) sensor material is shown in Fig. 9.

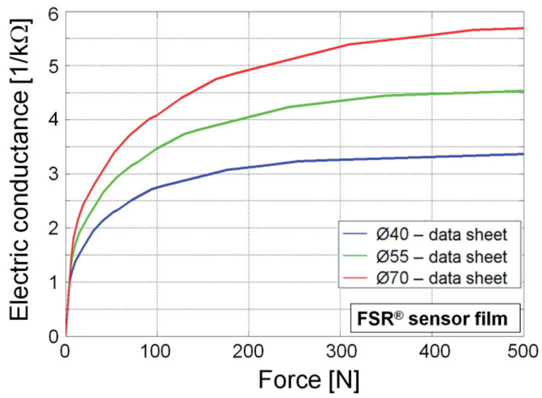

Fig. 8 Sensor characteristic of a piezoresistive sensor film [10]

A universal testing machine (Stable Micro Systems, TA.HD plus Texture Analyser) being able to register the applied load against time have been used for the mechanical loading. The controlling of the testing machine as well as the capturing of the measured load was performed with the aid of a PC being connected over serial communication interface (RS-232).

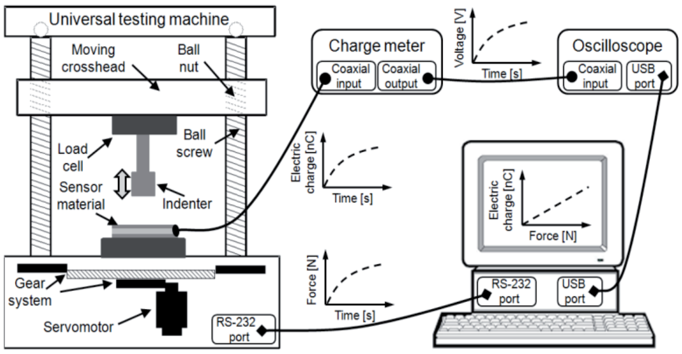

Fig. 9 Measurement set-up of the characterisation of PVDF and PP films

The generated electric charge of the sensor material was measured by a charge amplifier (Kistler Charge Meter, Type 5015A) being connected over a shielded coaxial cable. The estimated relative accuracy of the charge measurements was ~0.5%. The voltage output of the charge amplifier was captured with an oscilloscope (Agilent, DSO6034A) and the measured data was transmitted to the PC over serial communication interface (USB). Using the registered electric charge-time and force-time diagrams, the sensor characteristic can be calculated.

In case of the DEAP sensor film, the resulting capacitance change was measured by a precision LCR meter (HP 4274A Multi-Frequency LCR Meter) using four-terminal measuring technique. In general, the more accurate the measurement the more time it takes and conversely. Owing to the low sensor sensitivity of the DEAP material, the LCR-Meter was used in slow measurement mode and was calibrated before each measuring point to achieve a relative measuring accuracy of ~0.1% (in respect of the nominal capacitance of the measured sensor element) resulting in an absolute measuring accuracy of ~1.5pF. In case of the PVDF and PP materials, dynamic measurements were performed. In contrast to that, owing to the slower measuring speed of the electrical signal, the measurements of the DEAP material could be carried out only at static loads (in 100N steps).

In order to study the independency of the pressure distribution, the measurements were performed with three different flat-ended cylindrical indenters having a diameter of 40, 55 respectively 70 mm. In case of linear sensor materials, a force measurement being independent of pressure distribution, consequently overlapping sensor characteristics are expected.

All sensor films were shielded against electromagnetic interferences. Additionally, the PVDF sensor film was protected against thermal radiation and heat convection as well using reflective aluminium foil and thermal insulating polyurethane foam layers between the sensor material and the indenter.

In accordance with the electromechanical model (4), the PVDF film represents an excellent linearity as shown in Fig. 10.

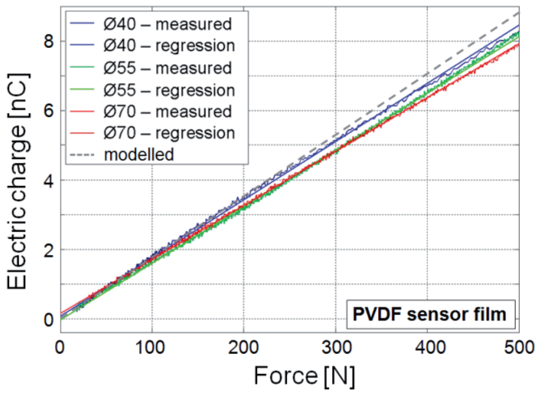

Fig. 10 Sensor characteristic of PVDF sensor film

In order to ease the evaluation of linearity, the linear regression curves of each measured characteristic have been presented as well. In spite of rigorous thermal shielding, the pyroelectric effect could not be eliminated completely resulting in a slight deviation between the measured and modelled curves.

In contrast to the product specification and the presented electromechanical model (12), the measured sensor characteristic of PP sensor film is strongly non-linear as shown in Fig. 11.

The non-linearity may arise from the inhomogeneous material and the non-uniform distribution of the permanent charges. The curves represent also the effect of non-linearity in terms of independency of pressure distribution. In some load ranges the deviation is more than 100% for the same load.

In spite of the non-linear electromechanical model, the DEAP sensor film shows a good linearity as shown in Fig. 12.

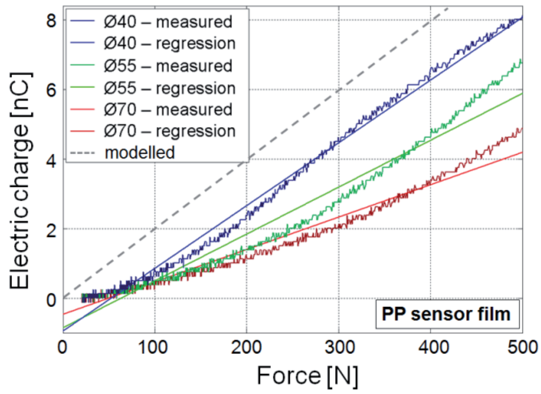

Fig. 11 Sensor characteristic of PP sensor film

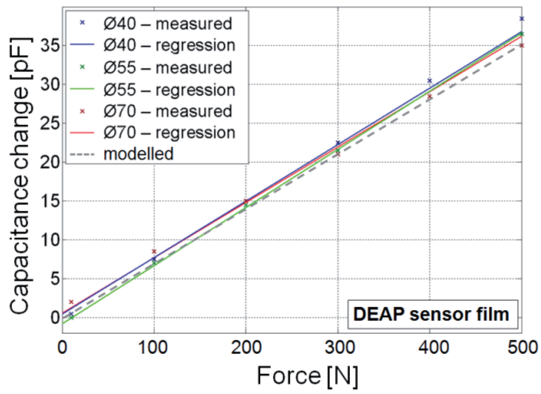

Fig. 12 Sensor characteristic of DEAP sensor film

The measured linear behaviour corresponds to the expectations as the derived electromechanical model (17) indicates a linearity error of less than ±2% in the applied load range (500N).

4 Evaluation of studied sensor materials

The evaluation of the studied sensor materials was realised with the aid of a decision matrix, which allows the systematically rating of the performance of the sensor materials in terms of applicability in a competitive large-area floor sensor application. The decision matrix consists of a set of weighted criteria. Weighting factors are used to define the level of importance of criteria on a scale from 1 to 5, where 1 is very low importance and 5 is very high importance as shown on Fig. 13.

	Weighting factor	Resistive sensor film	Cellular PP sensor film	PVDF sensor film	DEAP sensor film
Sensor linearity, Scalability	5	1	2	5	4
Noise sensitivity, Accuracy	5	2	5	1	4
Sensitivity, Complexity of evaluation electronics	3	5	5	5	3
Complexity of sensor matrix	4	2	4	2	4
Specific cost of sensor material	5	3	3	1	5
Patent situation	2	4	2	4	3
Weighted score		**61**	**85**	**66**	**96**

Fig. 13 Decision matrix

Criteria with strong dependencies on each other were merged and considered as a single criterion. The sensor linearity and scalability, the noise sensitivity and accuracy respectively the specific cost of the sensor material have been rated with very high importance as these sensor properties are essential for an application in a competitive, universal and accurate sensor network. The complexity of sensor matrix (e.g.: additional shielding or protective layers, complexity of wiring) and the complexity of evaluation electronics have been rated with high and medium importance respectively according to the share of total costs of the sensor network. Additionally, the patent situation in terms of manufacturing rights of the sensor materials has been rated as low importance.

Based on the weighted scores of the decision matrix and owing to the fact that only one sensor film fulfils the main criteria satisfactorily, the DEAP film appears to be the best candidate for the desired purposes.

5 Conclusion

In this study, four sensor materials working on piezoresistive, piezoelectric, quasi-piezoelectric and capacitive principle have been introduced and compared in order to find the most suitable solution for the detection of mechanical load in large-area floor sensor networks.

According to the presented comparison, for universal and competitive floor sensor applications, the usage of dielectric electro-active polymers is recommended instead of the conventional pressure sensitive materials such piezoresistive, piezoelectric or ferroelectret films.

The studied particular DEAP material possesses a good sensor linearity, scalability and noise sensitivity. Even the price of the sensor material samples being manufactured in prototypic volumes is much lower in comparison with the other available sensor materials but the applied roll-to-roll manufacturing technology and the lower raw material costs of DEAP (in comparison to the other sensor materials) allow a significant decrease of specific costs in case of larger production volumes providing a competitive technology for industrial applications (e.g.: surveillance or patient monitoring).

6 Future work

The first technology demonstrator using the presented DEAP technology has already been developed and was able to detect the movement of a person and to register the weight distribution on the surface of a floor sensor network consisting of 16 sensor elements distributed in a 4x4 sensor matrix [7]. Each sensor unit was 200x160 mm resulting in an overall sensor matrix size of 800x740 mm. The achieved measuring accuracy of the single sensor elements was around 5 kg. Although, this initial measuring accuracy is pretty low owing to the prototypical assembly of the sensor network, after improving the manufacturing process of the sensor network (which is supposed to increase the measuring accuracy) and increasing the number of sensor units, the implementation of higher level functions (e.g.: trajectory recognition, personal identification, weight analysis) can be realised. The improved floor sensor network could provide a technology platform for developing advanced applications (e. g.: orthopaedic step analysis, fall or intrusion detection).

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