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Flexible force sensors for e-textiles

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Abstract. This paper presents the development of inexpensive, lightweight, flexible polymer-based piezoresistive sensors appropriate for integration in e-textiles. The transducing element used is a volume-conductive carbon impregnated black polypropylene/polyethylene film with commercial names Velostat (from 3M) or Linqstat (from Caplinq). The objective is to investigate on the influence of different sensor constructions, varying film thicknesses, electrode materials and encapsulations on sensor performance. Furthermore, ways of integrating the sensors into textile products, as well as potential applications are also studied. In this paper, the behaviour of the sensors under different cyclic compression loads, applied at different speeds, is presented. Sensors using three different electrode materials are tested. The results show significant influence of sensor construction and electrode material on the static and dynamic performance of the devices.

1. Introduction

A force sensor based on piezoresistive conductive polyethylene film is composed of the transducing piezoresistive film and two electrodes, one on each side of the piezoresistive film, allowing for electrical connection. The electrical resistance of this assembly varies according to the force applied on it, thus allowing force sensing. Electrodes may be prepared, in theory, using any conductive material, such as metals, conducting textiles, conducting ink or other.

The development of a pressure sensor array for use in robotics, based on Velostat, was presented before [1]. Stripes of copper-coated fabric were used as electrode material. A matrix was formed by orienting the stripes on the upper electrode layer perpendicularly to the stripes on the lower one. The authors in [1] state that the resistance change depends on the electrical contact between electrodes and the conductive film rather than on the resistance change of the film itself.

Further work on this kind of sensors was presented in [2], where a model for piezoresistive sensors of this type was developed and tested against a sensor fabricated using copper plates as electrodes. The authors found that contact resistance is not very important at high resistance (low force) but becomes significant at low resistance. This means that the sensor construction and electrode preparation may have an important influence on the performance of the sensor.

An interesting construction for integration of this kind of sensors in textiles was developed in [3]. Using intarsia technique, a pocket was knitted in a single jersey structure, into which the piezoresistive



film was inserted. On each side of this pocket, an electrode area was produced using conductive yarn. The two electrode areas are connected using lines knitted with conductive yarn. The pressure-resistance dependence curve was obtained by applying controlled pressure with a compression probe and measuring the resultant resistance variations. The behaviour of this setup is very similar to the one used in [2].

In this work, a comparison between the different possibilities of sensor construction is carried out to define the most interesting possibilities for e-textile integration. The sensors are expected to be used as detachable parts in wearable electronics, or directly sewn to the textile.

2. Experimental

In a first phase, prototype sensors were constructed using a (30 x 30) mm² square of Velostat film. Electrodes were cut out from copper tape, ripstop conductive fabric (Sn/Cu/Ag plated polyamide fabric: Zell by Statex) and conductive knitted stretch fabric (silver-plated 94% polyamide, 6% Dorlastan: Medtex P-180 by Statex). The electrode dimensions were (25 x 25) mm², being this the active area of the sensor. The assembly was kept together by transparent adhesive tape; further encapsulation is achieved using 2mm-thick EPDM foam, which conveys mechanical protection to the sensing element. The sensor constructions are presented in Figure 1 (left). This paper presents the most important results of this first prototype phase.

In a later phase, electrodes will be produced by deposition of conducting metals (aluminium and nickel) by PVD (Physical Vapour Deposition) and using conductive inks. These processes should assure a constant contact resistance, limiting the sensor's response to the piezoresistive nature of the conductive polyamide film.

The sensors are tested using a Hounsfield dynamometer producing 10 cycles of compression between 2 and 100 N, 2 and 200 N or 2 and 500 N at a speed set at 5, 50 or 100 mm/min. Figure 1 (right) shows the setup for the cyclic compression test. The EPDM foam can be seen in this figure.

The sensor is connected to a Fluke 45 multimeter that acquires resistance values and transmits them to a PC via RS-232. In a second trial, the sensor is connected to a signal conditioning circuit that produces a voltage signal according to the sensor's resistance, as depicted in Figure 2.



Figure 1. (left): Sensors with conductive knitted stretch fabric (upper), conductive woven ripstop fabric (middle) and copper tape (lower) as electrodes. (right) Compression test setup

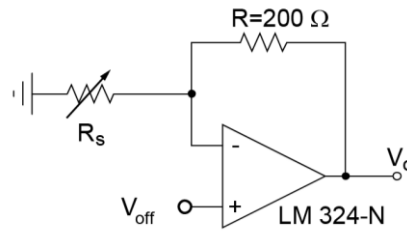


Figure 2: Conditioning circuit for the piezoresistive sensors, implemented with a non-inverting amplifier with gain dependent on the sensor resistance R_s

The relation between the sensor's resistance (R_s) and the voltage output (V_o) for the circuit used is expressed by equation 1:

$$V_o = V_{off} \left(1 + \frac{R}{R_s} \right) \quad (1)$$

with

- V_o : Output voltage (V)
- V_{off} : Offset Voltage (V)
- R_s : Sensor resistance (Ω)
- R : Feedback resistance (Ω)

3. Results and discussion

3.1. General behaviour of the sensors

Figure 3 shows the typical behaviour of resistance change with force, for a sample produced with copper electrodes (see Fig 1a), tested 10 cycles, between 2 and 100 N at 5 mm/min:

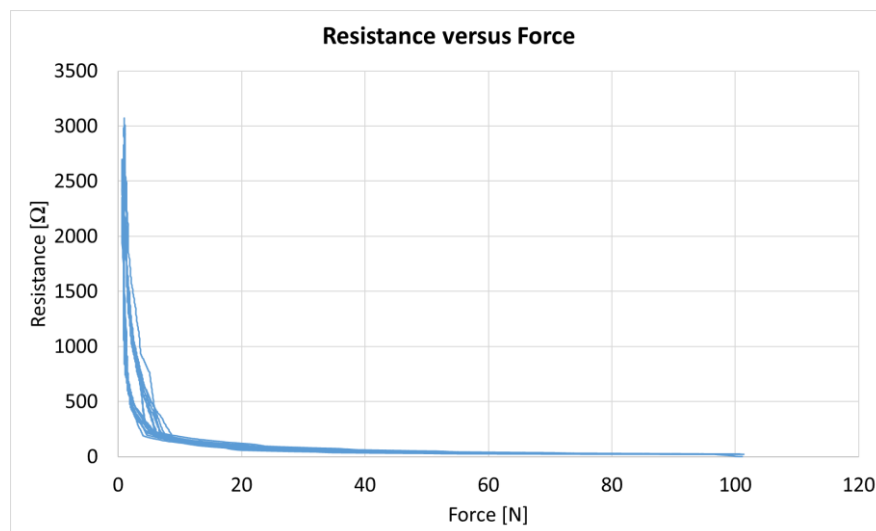


Figure 3: Resistance versus force obtained for a sample produced with copper electrodes, 10 cycles tested between 2 and 100 N at 5 mm/min

It can be observed that the resistance-force relation is non-linear, with very quick changes at low forces and slow change at high forces. The variation in resistance is very high, going from tens of $k\Omega$ to tens of Ω . To use the conditioning circuit of Figure 2 circuit, the small resistance values can be a challenge because of the high currents through the sensor R_S . To avoid this, V_{off} is set to a value of 0,1 V. Further reduction may render the circuit sensitive to noise.

Figure 4 shows the Force-Voltage dependence, using the output of the conditioning circuit.

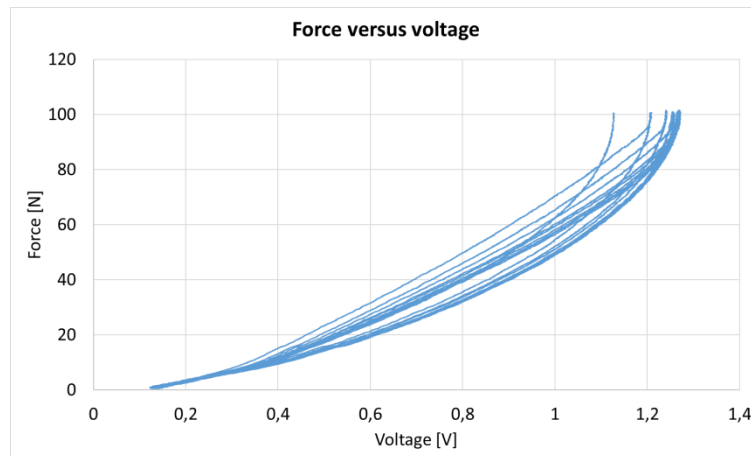


Figure 4: Force versus voltage obtained for a sample produced with copper electrodes, 10 cycles tested between 2 and 100 N at 5 mm/min

The resulting voltage-force curves are much closer to a linear function, with the conditioning circuit having an almost linearizing effect on the response, with a similar sensitivity (V/N) in all tested range. However, hysteresis is observed, mainly for forces above 20N.

3.2. Comparison of different compression speeds

Figure 5 shows the force/voltage curves obtained with the same sample, but using speeds of 50 (left) and 100 mm/min (right).

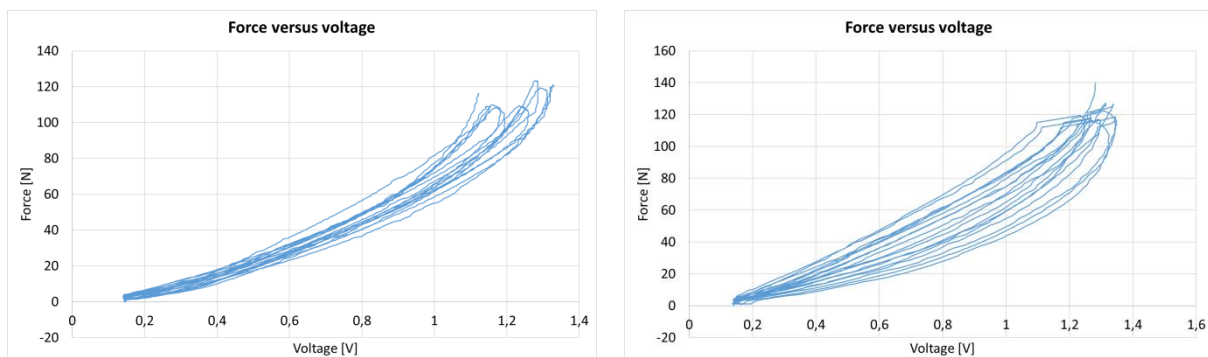


Figure 5: Force versus voltage obtained for the same sample used for results in Figure 4, 10 cycles tested between 2 and 100 N at 50 mm/min (left) and 100 mm/min (right)

Comparing the graphs of Figure 5 it can be seen that the spread of values and hysteresis increases with test speed. These results most certainly are due to the viscoelastic behaviour of the foam that does not allow the force variations to be quickly applied to the sensing element. In fact, the force vs displacement curves seem to confirm this hypothesis. Figure 6 shows these curves for the sample at 5 mm/min and 100 mm/min.

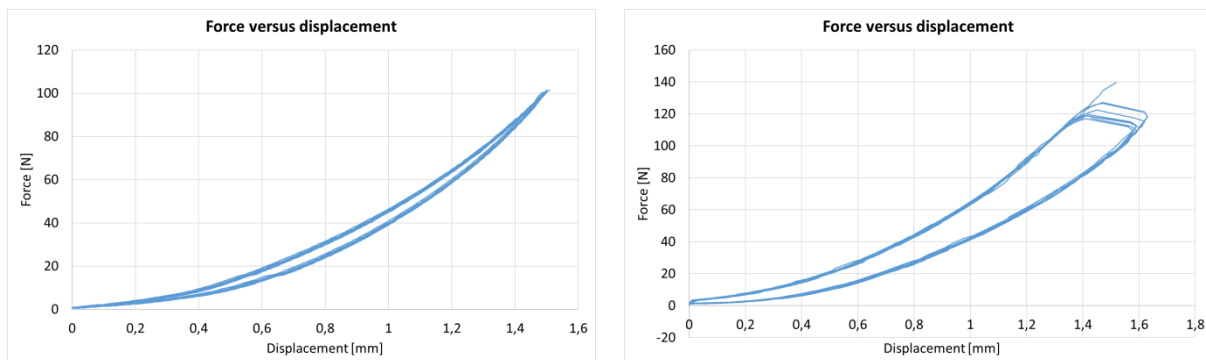


Figure 6: Comparison of force-displacement curves in 10 cycles, for the same sample at 5 and 100 mm/min

This type of behaviour has been consistently observed in all samples. If the sensor is to be used to make measurements of dynamic phenomena, a different protection material, with a more linear and elastic behaviour has to be used.

3.3. Comparison of electrode materials

Tests were performed to evaluate the behaviour of the sensor when different materials are used as electrodes. Figure 7 (left) presents the Force-Voltage dependence, using the conditioning amplifier presented, in a Velostat sensor with knitted (Medtex) electrodes, and Figure 7 (right), the same sensor device was fabricated with woven fabric (Zell) as electrodes. 10 cycles between 2 and 100 N were realized at 5 mm/min.

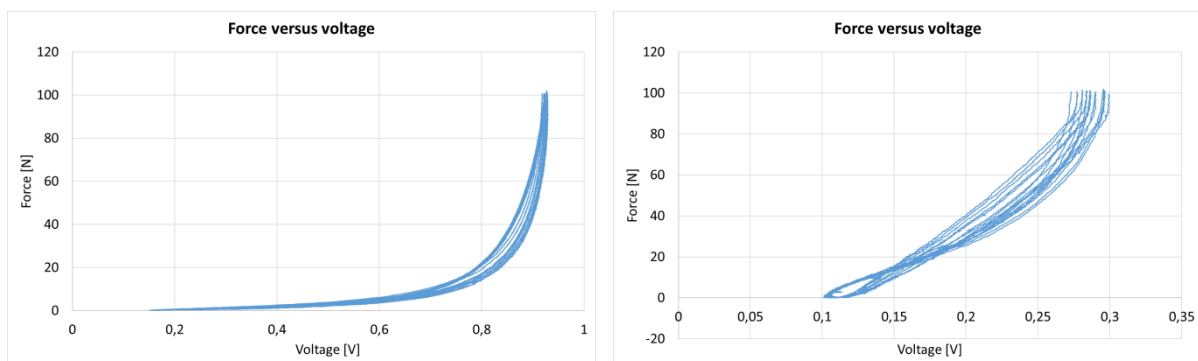


Figure 7: Force versus voltage obtained for sensors constructed with knitted (Medtex, left) and woven fabric (Zell, right) as electrodes, 10 cycles tested between 2 and 100 N at 5 mm/min

The comparison presented in Figure 7 is the most extreme case of difference found by using a different electrode material. The graphs clearly show that the contact resistance

electrode/piezoresistive film is of significant relevance and must be taken into account in the development of these sensors. Sensitivity and linearity are completely different when different electrodes are manufactured, despite the same sensor material.

The sensor with knitted material shows higher sensitivity and lower hysteresis, when compared with the sensor with woven fabric as electrodes. However, the second shows better linearity. A first analysis of the overall results shows that the knitted material seems to produce the most uniform behaviour of the sensor, despite its non-linearity. The result obtained with the woven fabric is similar to the one obtained with the copper electrode, except the sensitivity, which is lower for the fabric. Replacing the copper with the stretch fabric seems thus to be a valid option, and thus a higher degree of textile integration for these sensors can be achieved.

4. Conclusions

Three types of sensors, based on piezoresistive polymer have been tested and characterised in detail. The general principle of the transducer concept has been shown and the effect of different type of electrodes discussed - copper foil, knitted and woven fabric.

A conditioning circuit was used to convert resistance variation of the sensor to a voltage output, but also to linearize the behaviour of measured resistance with applied force. Some of the tested sensors present an almost linear behaviour after signal conditioning.

Future work will use PVD or conductive inks to produce the electrodes. Furthermore, conductive bonding materials will be used to join the textile electrode to the polymer film, which will provide yet another way to improve the sensor's behaviour. The protective foam used in this work, introduces some instability when applying dynamic stress. Alternative materials like natural rubber will be tested. Another aspect to be tackled is the measurement range of the sensors. Piezoresistive films with different conductivity and thickness may be interesting alternatives.

In this first assessment, many relevant aspects of sensor construction have been investigated and a detailed knowledge about the sensor behaviour has been acquired. Further work will allow the optimisation of the devices. Their integration into textiles is also being implemented, namely in equipment for the practice of martial arts.

Acknowledgments

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