Carbon Black Loaded Paper: an intelligent substrate for Electronic Sensors Design

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Abstract

Pressure and position sensors are usual components of many electronic devices. They equip cars and planes for security and presence sensing, industrial automated systems and many other Human-Interface Devices for medicine and kinesiology robotics, video games, etc. We present alternative ways to develop our selves these sensors using a low cost material: conductive paper loaded with carbon black pigments.

We show that such a paper can be easily used to develop position, pressure and flexion sensors and that it is a good basis to develop more refined sensors such as accelerometers or tilt sensors for shock sensing with smart packaging. We last compare a few trials to produce oneself this paper using conventional fibers such as TMP, chemical or recycled pulp using classic laboratory handsheet formers and mixing those with industrial carbon black loaded papers.

Keywords

Intelligent substrates; Conductive pigments; Piezoresistivity; Human Computer Interface.

1. Introduction

The most massively used flat pressure and position sensors are the Force Sensing Resistors (FSR) from Interlink Electronics Company, Camarillo, USA. FSRs are printed components and are composed of mixed polymers, organic pigments and metals. Unfortunately, due to their production process, they cannot be easily recycled. Moreover one can only have such sensors produced for minimal quantities corresponding to large-scale productions, and so, Interlink or most equivalent companies only develop sensors solutions for the massive industries introduced earlier.

Researchers and designers of Human Interface Devices who need only a few sensors have to find the appropriate one among those that were developed by major brands. They have to adapt their design to available sensors but they would prefer some customizable piezoresistive material that would enable them to design the size and shape of the sensor itself. This material would be inherently sensitive, available in rolls or sheet and so completely open to any shape or dimension for the user.

*Figure1: Various pressure sensors to be used or mounted onto a glove for musical application. One can also notice an example of homemade paper FSR on the left *.*

We have been looking for such materials [Koehly, 2005] and we have found that conductive paper would be an ideal candidate here. Loading paper with electrically resistive pigments such as carbon black provides us with an elastic and flexible volume resistive material, which simply needs to be placed between metallic electrodes (A1 and A2) to be used as a pressure (Figure 2), position or flexion sensor depending on the chosen design. Loading paper with conductive pigments does not prevent its re-use, as most papers are loaded with white pigments for optical properties, and we can recycle them similarly to produce cardboard or newspaper.

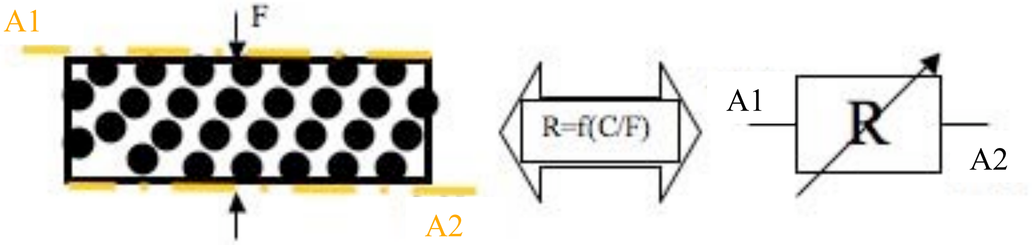

Figure 2: The resistance of carbon black loaded paper between two electrodes (A1 and A2) is function of the dimension of the electrodes (constant C) and is inversely proportional to the force applied onto the paper: R=f(C/F)

In a research project between EFPG in France and the department of Music Technology at McGill University in Canada, we have been studying conductive paper to be used as position and strain sensors. Our goal is to provide digital musical instrument designers with straightforward means to circumvent the limited offering of commercial sensors, which are restricted to a few technologies with predefined electrical characteristics, shapes and sizes [Jensenius, 2005]. Our goal is also to define the basis of possible applications of our sensors for advances in printing and media technology. For instance, we can imagine developing smart packaging for fragile packages that would integrate force sensors and tilts in case of shock. We also think on the development of printed conductors as far as connections are concerned.

2. Minimal considerations for building paper sensors

Carbon black loaded paper is a conventional paper that can be made using various types of fibers. The difference with other papers is mainly that it is loaded with carbon black pigments instead of the usual whitening pigments such as clay or $CaCO_3$. If one wants to develop a paper for a position sensor, the best paper will be highly refined and calendered to decrease as much as possible the surface porosity and roughness, as the aim will be to get a linear variation of electrical resistance along the surface. In reality, and as shown in figure 3, even a rough paper (industrial sample, thickness e=0.275mm, basis weight W=160g/m²) can provide sufficient linearity to develop a position sensor with a few mm resolution.

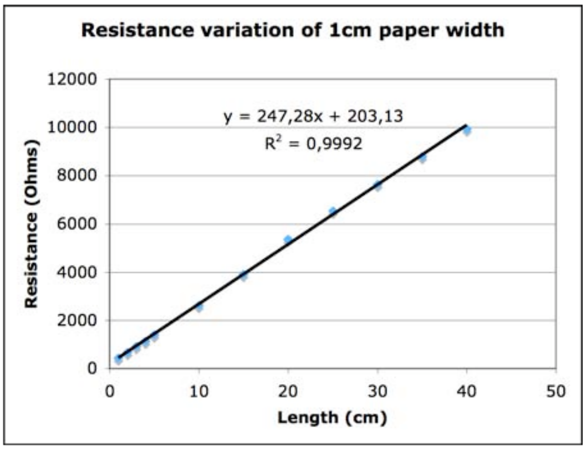

Figure 3: Even a rough paper provides sufficient linearity to develop a position sensor with a resolution under the pressure exerted by a human finger (2mm resolution equals around 50 Ohms).

Position sensors [Koehly, 2006] are made using three electrodes along a linear conductive sample. This sample can be any flexible support, inked or coated with an electrically conductive component or it can be a volume conductive material such as a band of conductive paper. One electrode is then fixed on each end of the band (figure 4). The resistance between the two electrodes A1 and A2 is then fixed and depends on the volume resistivity of respectively the ink coat or the whole conductive paper. The third electrode A3 is placed all along the conductive length, and provides a variable output proportional to the volume of resistive material that the current has to cross.

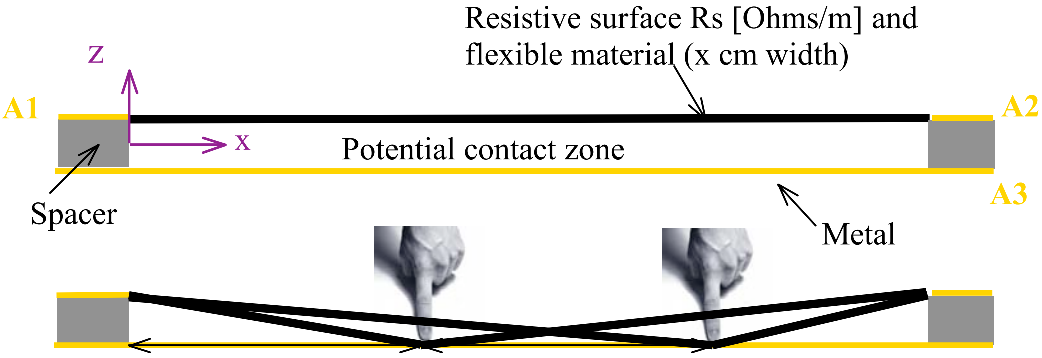

Figure 4: Schematic of a one-axis position sensor: pressing with the finger along the flexible resistive material creates a contact with the anode A3 that enables to obtain a value of the position of the sensor along the x-axis.

To develop efficient force or flexion sensors [Koehly, 2006], it is better to provide high roughness and porosity, as it is the volume resistivity and the surface contact variation that will mainly affect the resistance of the paper under strain. Pressure sensors are made using one or a stack of sheets of conductive paper between 2 electrodes. This sandwich would then act as a variable resistance, decreasing with compression. We show that this variation is partially due to the compression of the material along its thickness, and most mainly to contact surface variation between each sheet.

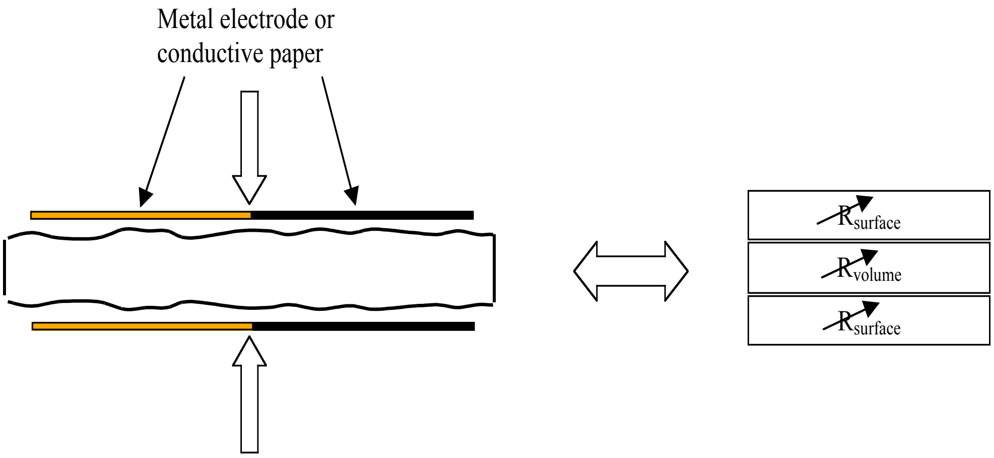

Figure 5: a conductive paper in between electrodes or other sheets of paper is equivalent to variable resistances in series, the variations of resistance being mostly due to surface contact variations (see later figure 8: the variation of resistance due to contact surface is 100 times more important than the one in volume).

A few sensors were developed using this configuration for which two conductive papers were investigated: One (paper G) was loaded with carbon and was thick (0.275mm, W=160g/m^2, 12,6% ash content for an ash test at 450°C) and the other (paper F) with graphite and was thinner (0.160 mm, 100g/m^2, 8.4% ash content). We varied the number of sheets stacked in order to see how we could extend the range of those pressure sensors; each stack was inserted between 2 copper plates used as electrodes. The paper samples were squares of 2.5cm^2 and the copper electrodes were 2cm^2 extended by a 1cm width plate to solder a wire. The whole was covered with some plastic film to prevent from moisture variations and copper oxidation. Figure 1 shows one of these sensors (*). 2 laboratory sheets were made from some repulped paper G with an English Sheet Former to increase its bulk.
Table 1 shows their range for each of those sensors. For instance, a sensor called 4G3F is composed of a stack of 4 sheets of G and 3 sheets of F. The table enables also to compare the range of the paper sensors to the range of 2 industrial sensors. For each sensors we give some values of a resistance to use to make a tension divider (usual electronic trick to adapt a sensor to the input tension). This enables to better compare the range efficiency between sensors.

Table 1: Comparison of the range for various homemade sensors to two industrial sensors for loads of 100g and 5kg. The samples were placed onto a weighing machine (compressed zone: 2cm^2) while the resistance was measured. It is possible to reproduce the same sensor using the same number of sheets stacked in a sandwich under 2 copper electrodes.

Paper	**3G**	**3G**	**3G**	**7G**	**4G +3F**	**4G +3F**	**4G +3F**	**Round FSR**	**Square FSR**	**1R**	**2R**
R at 100g (Ω)	550	450	500	1100	7, E 06	8, E 06	6, E 06	50, E 06	55000	2000	4000
R at 5000g (Ω)	18	17	22	41	28000	24000	30000	3400	200	19	42
ΔR (Ω)	532	433	478	1059	6972k	7976k	5970k	49996k	54800	1981	3958
ΔR/Rmean	1,87	1,85	1,83	1,86	1,98	1,99	1,98	1,99	1,98	1,96	1,96

We can first notice that we obtain a good reproducibility of the sensors looking at the samples 3G or 4G3F that were duplicated three times and all provide around the same range. We can also notice that industrial sensors can have quite a much wider range than the homemade ones. Last, we can see that increasing the number of sheets stacked enable to improve the range, but here again, there is a limit number of sheet to stack for optimal results. It is also interesting to notice that stacking the 2 sorts of papers (F and G) together provided the best results.

The industrial paper G was repulped and some new sheets were realised in order to provide a thicker fibrous mat and so to increase the range of resistance variation. the new paper was around 2.1mm thick for w=1200g/m^2. The bulk then increased from 1.67 cm^3/g to 1.75 cm^3/g. Experiments show (paper 1R and 2R) that we increased the possible range by this way (ΔR/Rmean went from 1.85 to 1.96), but we can not know if this is due to the difference in pigments concentration (11.2 % ash content for an new ash test at 450°C), the increase of the bulk or simply the increase of the basis weight or the thickness. We have then produced a series of paper based on paper G and three types of pulps: TMP and chemical pulp to see how this could vary the results in resistance variation.

3. Results & Discussion

We tried to improve paper G changing the pigment concentration and adding new virgin fibres to increase the elasticity of the fibrous mat. The major parameter that would influence the paper conductivity is the Carbon Black concentration. Preliminary ash tests (ISO 1762:1974) at 400°C on some samples showed the pigment concentration of the paper is between 15 to 20%. However, according to the papermakers, there is also some CaCO3 pigments in this paper, and an ash test does not able to differentiate carbon black pigments from the other ones. We then chose to produce new papers, increasing their thickness and their bulk by using bigger and less refined fibres. We used unbleached chemical pulp at 11°SR, and mechanical pulp at 66°SR to check that high refining would really be bad for paper elasticity.
Starting from some repulped paper G, we made 10 different pulps adding each time from 10 to 50% of each new pulp to the industrial one. From those pulps, we made each time two 500g/m^2 hand sheets (ISO 5269:1998) to check the influence of forming, pressing and drying. We expected to have higher bulk and lower pigment concentration for the "a series" than for the "b series". Table 2 shows some of the results.

Table 2: influence of the sheet formation and addition of new fibres into the conductive paper G.

Paper	% Paper G	%other pulp	Basis weight (g/cm^2)	Thickness (μm)	Bulk (cm^3/g)	% Pigments	% Porosity	Gram-mage (g/cm^2)	% Moisture	Resist. 10cm (Ω)
0a	100		630.8	1686	2.67	15.20%	74.0%	598.3	5.1%	575
0b	100		509.3	1019	2.00	12.10%	66.5%	476.4	6.5%	1500
1a	90	Chemical	660.8	1688	2.55	13.70%	73.1%	626.2	5.2%	▨
1b	90	Chemical	459.7	1039	2.26	10.30%	70.8%	429.9	6.5%	4700
2a	80	Chemical	658.2	1878	2.85	12.10%	76.2%	622.8	5.4%	▨
2b	80	Chemical	492.5	1162	2.36	9.50%	72.2%	460.5	6.5%	6000
3a	70	Chemical	645.9	1872	2.90	10.30%	76.9%	611.4	5.3%	1600
3b	70	Chemical	478.4	1193	2.49	7.60%	74.0%	447.8	6.4%	17000
6a	90	TMP	609.3	1615	2.65	13.30%	74.3%	574.7	5.7%	▨
6b	90	TMP	451.0	1061	2.35	10.60%	71.9%	421.3	6.6%	3700
7a	80	TMP	543.0	1331	2.45	11.80%	72.4%	514.4	5.3%	▨
7b	80	TMP	441.7	1033	2.34	9.60%	72.1%	410.2	7.1%	8200
8a	70	TMP	567.1	1325	2.34	10.10%	71.5%	534.5	5.7%	▨
8b	70	TMP	434.9	1012	2.33	7.50%	72.3%	405.9	6.7%	18500

Pigments concentration

Carbon black particles that are present in the paper enable it to be conductive. These pigments have the advantage to be very fine and very inexpensive. We can assume that the more a paper has pigments, the more conductive it will be. However, this is not the only parameter that will influence the conductivity. Indeed, we can also imagine that an increase in thickness, bulk or porosity will decrease the conductance. Figure 6 plots the resistance of the various samples. We can see that there is a clear but not direct link between pigment concentration and resistance value, and an exponential decrease of the resistance value with an increase of the pigment concentration. The variations are certainly due to the variations of the bulk and porosity between the samples (see table 2).

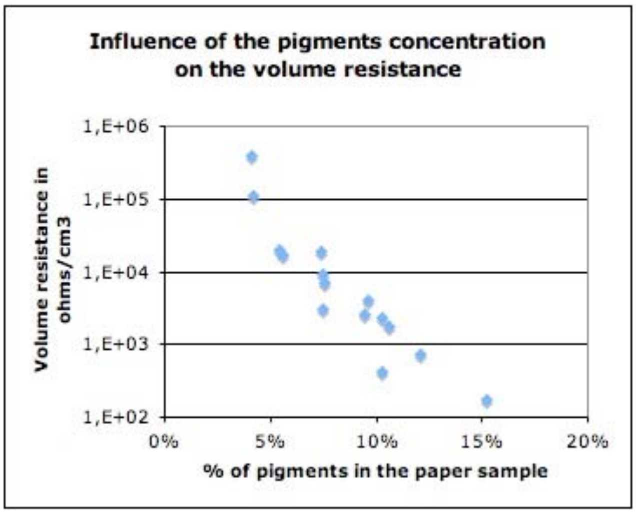

Figure 6: Variation of the volume resistance of various samples with the pigments concentration. The resistance was measured over samples of 10 cm length and 2cm width. The thickness varying between 1 and 2 mm, the values of resistance were normalised to the volume of the samples. Extracted from table 2 and other samples tested at lower pigments concentration.

Repeatability

A fundamental parameter for a sensor is its repeatability: the device should provide the same result in terms of resistance variation for the same applied compression. Conductive papers can provide such a characteristic because of their high compressibility and memory-shape property. If calibrated, i.e. if the paper is submitted to an excess of compression before its use, one can expect to obtain excellent results with a paper force sensor for various forces as long as one does not exceed the compression load.

We mentioned earlier that the resistance variation would mainly be due to surface contact variations and much less to the volume compression of the paper. We then developed an apparatus (figure 7) enabling to control the pressure on a defined zone of the paper (4 or 10cm^2) and measure the variation of conductivity. The sample was placed on a high sensitivity pressure sensor that would send the pressure value applied on the sample to the computer. A pneumatic system was controlled by the computer to apply a force of 0 to 60 Newton through a pneumatic jack on which was screwed a flat contact piece (5*2cm^2) that would distribute the pneumatic force along a defined zone over the paper sample (4 or 10 cm^2 depending on the contact piece orientation). The contact piece in metal would vary the conductivity of the paper sample and provide information on the variation of resistance due to contact surface variations. This apparatus does not work efficiently for less than 4 Newton, because of some friction forces in the pneumatic jack. This system enables to plot the variation of Force vs Conductance on a scale of 4 to 60N.

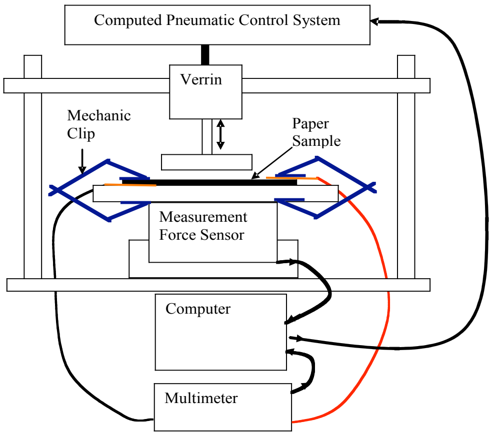

Figure 7: Sensor testing apparatus developed at the EFPG by the LGP2

A first trial was made on paper G to determine the influence of the resistance variation in volume and the one in surface in surface. For the test in volume, the contact piece was covered with an insulator. Figure 8 shows the results: while the variation of resistance in volume is only a few ohms, the variation in surface is around 300 ohms.

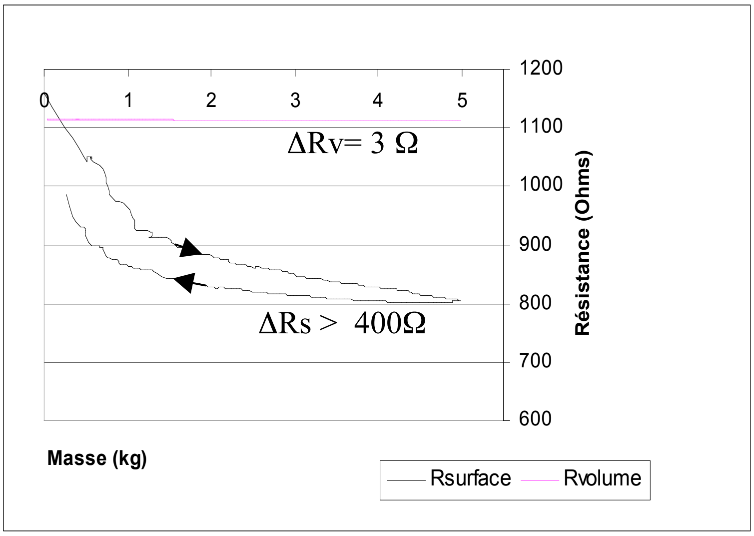

Figure 8: Variation of resistance for sample G tested with the apparatus of figure 7. When the contact piece is insulated, we can only notice a few Ohms resistance variations, whereas when it is not, the resistance variation drops from more than 1100 ohms to 800 ohms for a load gradually applied from 0 to 5 kg and return (compressed zone 4 cm2).

We can also notice the hysteresis that is generated when compressing and releasing the force applied which is inherent to any material in compression that is not purely elastic. Other industrial sensors would suffer the same drawback. Also, the variations at the beginning of the test are due to the apparatus: when the friction force of the jack is passed a sudden load is applied onto the paper and the system has to readjust to the setting. However, it is interesting to see the results given over a few trials to check the repeatability of the measurements for the same load setting. The test of figure 9 shows that, after a first loading, that is different from the following (i.e. calibration test), the other trials are very similar thus providing a good repeatability for the measurement of varying force from the paper G.

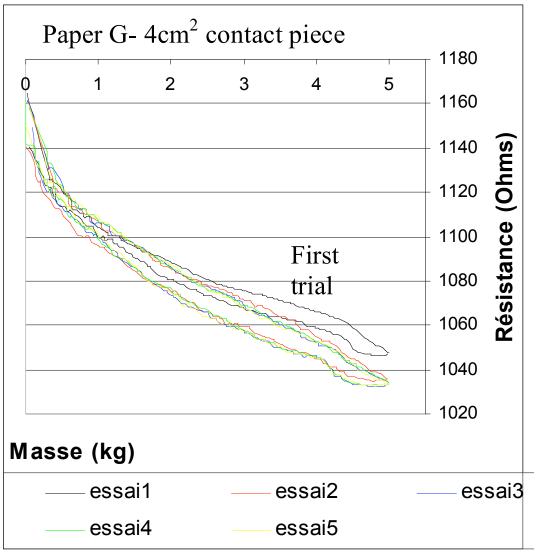

Figure 9: repeatability test: after a calibration load the paper will provide the same resistance variation for the same applied force, and this as much when loading than when unloading.

Influence of the fibres

The influence of the fibres is not easy to determine. Indeed, we did not make sheets with various pulps and having the same pigment concentration, except for samples 3b and 8b:

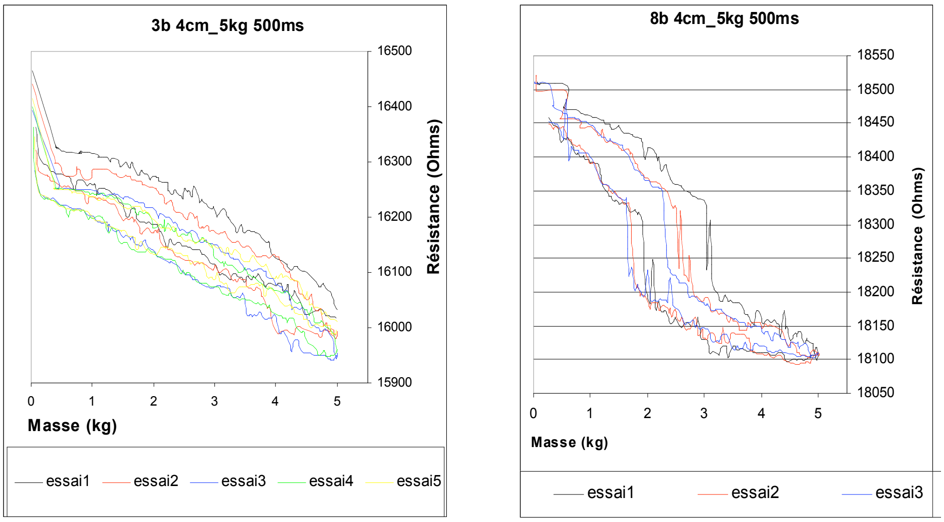

Figure 10: influence of the fibres on the linear response of the resistance variation. 30% of chemical pulp and TMP were added respectively for papers 3b and 8b. We can see that long and less refined fibres enables better linear results and elasticity.

Sheets 3b being made with chemical pulp and sheet 8b with TMP, we can notice the importance of using long and less refined fibres to obtain linear results and fibre elasticity. Indeed, the results for sheet 3b is much better than for 8b in terms of linearity for 4cm² loading surface.

4. Perspectives & conclusion

We could notice that some industrial papers such as paper G already provided good results in terms of repeatability for various applications. Another important point to use sensors for "expert" control gesture or dynamic measurement is its time-response, which means the time the material takes to come back to its original position and conduction response after being loaded. We measured this with an oscilloscope and noticed that it takes 75ms for the sensor to come back to a steady conductivity value when the pressure is released. This means that we can not measure with precision two data under this time interval. Then, if we build for instance an electronic percussion, the sensor will enable to detect around 13 hit per second. A professional percussionist might go faster than the sensor when he drums, but for toys and no professional quality, this time-response would be sufficient for such an application. As far as tilts sensing for packaging applications is concerned, it is also interesting to have a low time response as the sensors should detect quick shocks due to bad manipulation during transportation.

New papers will be developed as well as another method to measure the content of pigments such as using a thermogravimetric analyer. Paper G will be kept as a basis of material and lower concentrations of long fibres such as chemical pulp will be added to improve its bulk, trying to find a compromise between an optimised range, good repeatability and low hysteresis for the optimised sample.
Another machine will also be built to enable better measurements, replacing the pneumatic jack by an electrically driven worm, thus eliminating the problem of friction and bad measurements under 4 Newtons.

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