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IMPACT OF FABRIC PARAMETERS ON THE TEXTILE DIELECTRIC LAYER OF A CAPACITIVE PRESSURE SENSOR

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IMPACT OF FABRIC PARAMETERS ON THE TEXTILE DIELECTRIC LAYER OF
A CAPACITIVE PRESSURE SENSOR

BY

JAIME FINE

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE
REQUIREMENTS FOR THE DEGREE OF

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OF
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2019

ABSTRACT

Porosity variations in a non-textile dielectric layer are known to impact sensor output in a capacitive pressure sensor. There are many benefits to using completely textile-based sensors for wearable technology, such as comfort, washability, cost, and ease of integration. Therefore, this study intended to establish if differences in structural parameters and air permeability of a textile-based dielectric layer could influence sensor output as well. The thickness of various polyester, nylon, and acrylic fabrics was determined via ASTM D1777-96 (2015): Standard Test Method for Thickness of Textile Materials. Several fabrics of similar thickness within each fiber group were selected to be conditioned in accordance with ASTM D1776: Standard Practice for Conditioning and Testing Textiles before being tested for air permeability under the guidelines from ASTM D737-18: Standard Test Method for Air Permeability of Textile Fabrics.

The chosen fabrics were cut to 108x108mm. These textile samples were sandwiched between two 2x102x102mm stainless steel plates and attached to an LCR meter. Weight was applied to these sensors in 500g increments up to 4000g and then removed in 500g increments back to 0g. Six trials were conducted for each fabric. Hysteresis error, sensitivity, linearity error, and repeatability were calculated from the data. The results showed that structural variations did cause distinct differences in sensor output. However, there was not enough control in the structural variations to determine specific trends. Further testing with more controlled structural variations would also be necessary to determine the impact of air permeability.

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CHAPTER 1

INTRODUCTION

E-textiles are based on the incorporation of electronics, such as sensors, into garments. Innovative minds continue to find new uses for smart textiles in a wide variety of fields, including the medical, fashion, and gaming industries. Some of these sensors are based on a variation in capacitance as the textile is manipulated. Many studies using non-textile materials for the dielectric layer (spacer) of such capacitive sensors have shown that manipulating the porosity and the compressibility of the spacer can beneficially impact sensor output. However, the methods of modifying non-textile dielectric materials can be intricate, costly, and time-consuming [1], and it is preferable to integrate textile-based sensors into clothing for improved comfort, washability, and ease of integration. Textiles can effectively be used for the spacer of capacitive sensors, but their porosity and compressibility (and hence their capacitance) can change with the nature of fiber, yarn, and fabric. This study aims to investigate how constructional variations in the fabric used as a dielectric layer influence sensor output.

The e-textile market is currently valued at \$100m in annual wholesale revenue and is expected to reach \$5b by 2027 [2]. As prices of manufacturing and electronics have dropped, the popularity of wearable technology has risen [3]. Both Google and Apple have increased their e-textile investments, and Google has even teamed up with Nike to produce athletic shoes that can track footsteps via Google Earth [3]. Wearable

technology is also improving healthcare by way of telemedicine. A doctor can remotely monitor their patients' symptoms, cutting down on clinical visits, and providing doctors with a complete look at an individual's health [4]. When using sensors for continuous monitorization they should preferably be integrated directly into clothing because attachment is simple and more convenient for the user [5]. A table reviewing various implementations of textile sensors can be found in Appendix A.

Changes in response to an applied force can be measured by deviations in piezoelectric, piezoresistive, and capacitive values. Piezoelectric pressure sensors use piezoelectric materials, which create a voltage in response to mechanical deformation, whereas piezoresistive sensors use semiconductive materials that change resistivity [6, 7]. Capacitive sensors use nonconductive (dielectric) materials to store charge in conductive materials, and this charge varies in response to compression of the dielectric material [8]. Images of capacitive pressure sensors can be seen in Appendix A. Capacitive sensors are simpler, cheaper, more accurate, and more reliable than piezoelectric and piezoresistive [9, 10]. Therefore, this study will focus on capacitive pressure sensors.

Capacitive pressure sensors usually consist of a dielectric material sandwiched between two conductive plates (electrodes). The spacer allows a charge to be stored in the conductive plates, and this ability to store charge is known as the capacitance. The capacitance is inversely correlated to the distance between the two electrodes. Therefore, when pressure is applied to the sensors, the distance between the two plates decreases, and the stored charge increases. Once calibrated, this change in capacitance

can be used to determine the amount of pressure applied. See Figure 1 for a diagram of a capacitive pressure sensor. This is represented in the following formula [8]:

$$C = \epsilon_0 \epsilon_r \frac{A}{d}$$

C is the capacitance of the sensor, ϵ_0 is the free space's dielectric constant, ϵ_r is the spacer's dielectric constant, A is the overlapping surface area of the parallel plates, and d is the distance between those plates [8]. The dielectric constant, also known as relative permittivity, is the material's ability to store a charge [11]. When textiles are used, the type of fiber, surface area, and thickness of the material used for the dielectric spacer heavily impact the capacitance of the sensor, and therefore affect sensor output.

Figure 1. Diagram of a capacitor circuit and functional principle.

The dielectric material's deformation under compression strongly influences the sensor's pressure sensitivity. Sensitivity can be calculated by the following formula [8]:

$$S = \frac{(\Delta C/C_0)}{\Delta P}$$

Where S is sensitivity, ΔP is the change in pressure applied, C_0 is the baseline capacitance value when no force is used, and ΔC is the change in capacitance after the application of pressure [8].

The modification of non-textile dielectric structures controlling sensor output has been studied with promising results. The porosity of non-textile dielectric materials can be altered to improve sensitivity, with rough interfaces, micropillar arrays, or microscale pyramids [1]. Increased porosity improves sensor sensitivity by reducing stiffness and therefore increasing compressibility [12]. Additionally, the air pockets in the spacer act as a component of dielectric layer that can be compressed, even further improving sensitivity [12, 8, 1]. The resulting increase in sensitivity may not be consistent across all ranges of pressure. A study using capacitive pressure sensor insoles with a porous-silicone dielectric layer to continuously monitor the human gait found that at a low-pressure range, the air gaps were fully open, and therefore the sensors were most sensitive [8]. The capacitance was affected by both the change in distance within the micropores and the change in distance between the electrodes. As the applied pressure increased, the air gaps fully closed, and the capacitance was only affected by the change in distance between the two electrodes [8]. Since silicone is a rubbery material, it will likely maintain more compressibility than textile materials once all its micropores are closed.

While any dielectric material can be used for the spacer layer of a capacitive sensor, it is preferable for sensors used in wearable technology to be entirely

composed of textiles as this improves comfort, ease of integration, and washability [5]. Images showing examples of textile capacitive pressure sensors can be seen in Appendix A. Much research has shown how factors, such as fabric construction method, weave density, yarn fineness, and filament fineness can impact a fabric's compressibility and porosity [13]. One study tested the compressional properties on woven fabrics with five different weave patterns and three different weft densities [14]. The thickness and recovery of these fabrics were measured at various pressures and were shown to depend on the weave pattern and the weft density. Investigating if these variations are significant enough to impact sensor output is the next logical step.

Any cyclic loading and unloading sequence can exhibit hysteresis, which is the discrepancy in measurement when a force is applied in increasing and decreasing values [15]. Since a fabric's speed of recovery can depend on its structure it is possible that construction method will impact hysteresis error. A study using a resistive textile strain sensor showed that hysteresis could result from friction and structural deviations within the fabric [16]. Similar distortions might occur from the application of pressure.

When all other aspects of fabrication are kept constant, variations in yarn construction impacts air permeability. The amount of twist in the yarn, the size of the yarns, the type of yarn structure, and fiber length all play a role [17]. For a given fabric count and yarn count, using yarns with a higher twist per inch (TPI) increases air permeability because it increases the gaps between yarns [18]. A yarn's texture impacts its volume, and thus textured yarns have a higher permeability than flat yarns [19]. This additional volume created by textured yarns can also increase

compressibility [20]. Fiber length also measurably impacts air permeability. Yarns composed of staple fibers are hairy and must be spun to keep the fibers together. This hairiness can cover the gaps in-between yarns, thus disrupting air-flow compared to fabrics of the same structure composed with filament yarns [21].

Along with hysteresis, structural variations have the potential to impact sensitivity, range, linearity, and repeatability of the textile-based capacitive pressure sensors. Sensitivity is the smallest detectable amount of change in pressure. Range is the minimum and maximum detectable pressure values. Linearity error is the degree to which the actual sensor output curve varies from its line of best fit. Linearity error helps to show the predictability of the sensor and helps to break down the full range of a sensor into smaller, more functional ranges for practical uses. Repeatability is the sensor's ability to produce consistent results over the span of multiple trials.

This study serves as a preliminary study of the relationship between textile structure and variations in sensitivity, range, hysteresis, linearity, and repeatability of the textile dielectric layer of a capacitive pressure sensor. Possible trends between sensor output and air permeability will be examined.

CHAPTER 2

METHODOLOGY

Materials:

- Two 2x102x102mm stainless steel plates
- BCP Double Sided Adhesive Conductive Tape
- 102x102mm plastic square
- Container (279x114x114mm)
- Assorted Polyester, Nylon, and Acrylic Fabrics
- Acetone
- 90% Formic Acid
- Dimethylformamide (DMF)

Equipment:

- FX 3300 Air Permeability Tester (TEXTTEST)
- Capacitor discharge pen
- Elenco CM1555 Digital Capacitance Meter
- Thickness Gage
- Thread counter microscope
- Conditioning racks
- King Universal Manual Sample Cutter

Fiber Identification:

For this experiment, the spacer materials were only synthetic fibers (specifically polyester, nylon, and acrylic) as they tend to have lower moisture regain and therefore are less impacted by humidity. Mohawk Fabrics provided three polyester knits and the University of Rhode Island's Textile Science Lab provided the other 22 fabrics. The 25 fabrics were assigned a number for the convenience of the researcher. Fiber identification was performed using the solubility and burn tests from AATCC Test Method 20 [22].

Fabric Characterization:

Thickness was assessed according to ASTM D1777-96 (2015): Standard Test Method for thickness of textile materials, via thickness gage [23]. The measurement was taken from ten different locations for each fabric. Since fiber content and thickness are known to affect functionality of the dielectric layer, fabrics of the same fiber content with similar thickness (within 50 microns) were selected for sensors. The construction method of the chosen fabrics was determined visually. Further characterization testing was performed to determine fabric count, fabric weight, and fiber density in consideration of those who may continue this research. ASTM D3775-17e1, Standard Test Method for End (Warp) and Pick (Filling) Count [24] and ASTM D3774: Course Count of Knitted Fabrics [25] were used to determine count, and ASTM D3776: Fabric Weight [26] was used to determine weight. Normally, for ASTM D3776, a sample that runs the full width of the fabric is folded three times and cut with a cutting die and weighed. Due to limited supplies of fabric, only one circle

was cut and weighed. That value was then multiplied by eight and converted to g/m^2 .

Testing for air permeability:

Four specimens (a bare minimum of 153x153mm) were cut from each fabric. Ideally the specimens would be broadly distributed across the length and width, along the diagonal of the fabric; however, they were cut in close proximity to each other due to limited supply of materials. The specimens were then placed on conditioning racks, for four hours in a room with $21\pm 1^\circ\text{C}$ and $65\pm 2\%$ relative humidity, in accordance with ASTM D1776: Standard Practice for Conditioning and Testing Textiles [27] ASTM D737-18: Standard Test Method for Air Permeability of Textile Fabrics was performed under the same temperature and humidity conditions [28]. The test apparatus was set to a pressure drop of 125 Pa, in line with ASTM testing specifications. Density was determined by calculating the volume of that circle and dividing its weight by its volume.

Sensor construction:

The chosen fabrics were cut to 108x108mm. These textile samples were sandwiched between two 2x102x102mm stainless steel plates. Metal plates are rigid and stable and will maintain a constant surface area, which reduces error when performing the experiments. One tab of conductive tape stabilized by cardboard was attached to each metal plate as connections for the sensors. The same two plates were used throughout. This set up can be seen in figure 2. A discharger was applied to the

metal plates between trials to discharge any remaining stored charge. This process can be seen in figure 3.

Figure 2. Diagram of sensor setup. Figure not drawn to scale.

Figure 3. Diagram of discharge process. Figure not drawn to scale.

Preliminary testing:

Test parameters were determined in preliminary testing in which only fabrics with the same fiber content and a similar thickness were compared to be certain that any differences in sensor output resulted from textile structural variation. A spec sheet for these fabrics can be found in Appendix B.

Force was applied via a plastic container placed on top of a plastic square with the same dimensions as the metal plates (102x102mm). After constructing the sensor, both tabs were attached to the capacitance meter. Initially, weight was added by pouring water in 500g increments in one minute until the load reached 2500g. During the preliminary testing process, the researcher concluded that water would be too difficult to use and opted to switch for 500g sandbags. The weight range was changed to 500g-4000g in order to be more informative when comparing changes in sensitivity. The capacitance reading stabilized within 20 seconds or less for each fabric, so a time interval of 30 seconds was used for subsequent testing. This process can be seen in figure 4.

Figure 4. Diagram of weight application. Figure not drawn to scale.

Sensor Testing:

Six trials were run for each of the 12 fabrics selected. Weight was added in 500g(0.479kPa) increments, every 30 seconds, until the maximum load of 4000g (3.83kPa) was reached. Then weight was removed in 500g increments, every 30 seconds, until the load was down to 0g. Hysteresis error was calculated from the loading and unloading data. Sensitivity, linearity, and repeatability were calculated from the loading data.

Hysteresis Error:

The data from the six trials was averaged and then the following formula was used to calculate hysteresis error [29]:

$$\delta H = \frac{\Delta H_{\max}}{Y} \times 100\%$$

Where δH is hysteresis, $\Delta H_{\max}$ is the maximum difference between loading and unloading, and Y is the full-scale output of the sensor.

Sensitivity:

The following formula, previously referenced on pg. (3), was used to calculate sensitivity between 0-500g(0-0.479kPa) and between 3500-4000g (3.35-3.83kPa):

$$S = \frac{(\Delta C / C_0)}{\Delta P}$$

Linearity Error:

For linearity, the loading data was broken into two sections, 0-1000g (0-0.958kPa) and 1500-4000g (1.44-3.83kPa) since the error is typically calculated from the most linear portion. The data was graphed and the line of best fit was determined. The error was then calculated using the following formula [29]:

$$\delta_L = \frac{\Delta Y_{\max}}{Y} \times 100\%$$

Where δ_L is linearity, $\Delta Y_{\max}$ is the maximum deviation between the capacitance curve and the line of best fit, and Y is the full-scale output.

Repeatability:

The standard deviation for each weight increment was calculated from all six trials. The mean of the standard deviations for all nine weight increments served as the repeatability value.

CHAPTER 3

RESULTS AND DISCUSSION

Figure 5. Graph of sensitivity for fabrics in Group 1.

Group 1's sensitivity results are shown above to represent the sensitivity variations seen amongst the different groups. Fabric 10 had an air permeability value of 269cfm, more than twice that of Fabric 12's air permeability of 121cfm. However, as seen in the graph above, Fabric 12 is notably more sensitive than Fabric 10. These results cannot be explained by the minimal differences in thickness between the fabrics, since Fabric 12 is also thicker than Fabric 10. These results indicate that there must be other structural parameters, beyond air permeability, impacting sensitivity. There was no consistent trend between air permeability and sensitivity in groups 2, 3, or 4, although the results also indicated that structural variation does have an impact.

Table 1. Group 1's fabric structure, air permeability, total linearity error, linearity error between 0 and 0.958kPa, and linearity error between 1.44 and 3.83kPa.

Linearity error					
Group 1					
Fabric #	Structure	Air permeability (cfm)	total error	0-0.958kPa	1.44-3.83kPa
4	weft jersey knit	632	26.2%	6.00%	3.71%
10	warp tricot knit	269	18.7%	8.19%	3.87%
12	plain weave	121	25.2%	11.0%	7.64%
19	twill weave	8.93	17.5%	4.79%	4.63%

Observing the linearity error further illustrates how various structure parameters beyond air permeability are affecting sensor output. In studies using non-textile dielectrics with added porosity, when the air pockets close, there is a decrease in sensitivity, which would in turn increase linearity error [8]. Looking at the relationship between air permeability and overall linearity error in Group 1, one can see that there is not a direct correlation between the two. Fabric 10 has air permeability of 269 cfm and an overall linearity error of 18.7%. Fabric 12 has air permeability of 121 cfm and yet has a considerably higher linearity error of 25.2%. This could be indicating that variations in fabric and yarn structure are causing the air pockets to compress at different rates.

Figure 6. Graph of hysteresis error for fabrics in Group 1.

There was no clear pattern between hysteresis error and air permeability. Studies show that types of knit or woven patterns and variations in fabric count have an impact on compression recovery [14]. Although there were not enough controls in the construction parameters in this study to determine how they impact hysteresis error, the results do show distinct differences between fabrics within the same groups.

Figure 7. Graph of repeatability for fabrics in Group 3.

Repeatability also seemed to vary between within each group, without an obvious link to air permeability. User error may account for some of the discrepancies, however, structural components likely play a large role as well.

While performing characterization testing, it was discovered that Fabric 2 and 3 are likely the same fabric from different bolts. Although the inconsistencies in their structures were minimal, there were noticeable differences in sensitivity and linearity at a lower pressure range, as well as in repeatability. Further research should be done to see if small variations in manufacturing can cause significant discrepancies in sensor output as this can be a concern when mass producing textile-based sensors.

The rest of the tables and graphs can be found in Appendix B.

CHAPTER 4

CONCLUSION

Evaluation of the sensors for sensitivity, linearity, hysteresis, and repeatability shows that structural parameters of the textile dielectric layer can impact sensor output although; air permeability is not a reliable predicting factor. While a higher air permeability value would indicate greater volumes of air pockets to act as an additional dielectric layer, it does not determine the quantity of air pockets or how the pockets will compress under a given pressure. This study could not definitively show a connection between sensor output and air permeability. However, it does support the theory that structural variations in fabric can impact output.

The fact that there was no consistent trend between sensor output and fabric structure is an important finding in itself. These results do not necessarily dismiss the role of knit and weave patterns in capacitive pressure sensors, but rather show that many other elements of fabric are also relevant. This is significant in terms of sensor applications because it means that there is potential to combine different fabric construction qualities in order to pick a material that is ideal for the end-use of the e-textile while still meeting the data collection needs of the sensor.

These findings are very promising and suggest that additional research would be beneficial for the world of wearable technology. Fabric structure can vary in many capacities, such as fiber length, turns per inch in yarn, fineness of yarn, thread count, weave or knit pattern, and more. Further studies with control over these structural

parameters would be necessary to determine which factors are most influential and what specific impact they have on sensor output. For example, qualities such density and weight may alter how air pockets compress, which could in turn impact linearity. Such studies could offer clarity when choosing textiles that meet both the needs of the sensor and the needs of the garments that the sensors are being integrated into.

One recommended area of study would be fabric compressibility in relation to range, sensitivity, and linearity. In non-textile based pressure sensors, using a more compressible dielectric material can improve sensor range and sensitivity, so it is likely that fabrics would follow a similar trend. Additionally, possible trends between compression recovery and hysteresis error and repeatability could be explored. Textiles with poor compression recovery may have a greater lag between increasing and decreasing loads so it is possible that compression recovery could be a predictor for hysteresis error. Furthermore, testing compressibility could potentially offer more understanding of the role of air permeability. Fabrics with varying air permeability and similar compressibility and fabrics with similar air permeability and varying compressibility could both be compared to see if either factor has greater impact on sensor output.

Along with testing for influential fabric qualities, it would be useful to do additional testing for sensor proficiency. The sensors can be laundered and subjected to other wearable simulations before being tested to decide which materials would function best for different uses. The sensors could also be put through repeated trials to explore longevity. Other recommended tests include testing for full range and

repeatedly adding and taking away the same amount of weight in order to see how the fabric responds in different applications.

This research offers a preliminary look at the potential for manipulating sensor output of capacitive pressure sensors via variations in structural parameters of a textile-based dielectric layer. The results show that differences in structure do impact sensor output. Further exploration is necessary to determine which aspects of structure alter sensor output.

APPENDIX A

Examples of Sensors

Table 2. Examples of existing research on fabric sensors

Reference	Year	Functional Principle	Matrix/Single	Materials	Usage
[30]	2018	Piezo-resistive	Single (2.5x3.5cm)	Conductive Shieldex NoraDell woven fabric sheets, Low Density Polyethylene sheet	Finger tips of gloves for measuring pressure of grip
[5]	2010	Capacitive	Matrix 240 elements (430x450mm)	Silver coated woven textiles, polyester foam spacer	Seat for Posture Monitoring
[12]	2018	Capacitive	Single (15x15mm)	Conductive knit fabric, microporous silicone spacer	Gloves for monitoring grasp, and potential soft wearable robotic uses
[16]	2006	Piezo-resistive	Matrix	Polyacrylonitrile yarn knitted into a fabric	Possible uses include: monitoring body movement, pulse, and blood pressure as well as industry strain gauges for planes
[31]	2014	Capacitive	Single (830x38.6mm)	Polyester fabric plated with nickel and copper, polyester fusible woven interlining	Monitoring respiration
[32]	2016	Piezo-resistive	Matrix 32x32 sensing elements (39x39cm active area)	Cotton fabric, silver coated conductive yarns	Telemedicine: remotely monitor patients with limited mobility
[33]	2013	Capacitive	N/A	Hollow woven conductive fibers	Pressure sensor on mattress to monitor ulcer patients. Shoe insoles to monitor gait analysis and athletes for training purposes

Figure 8. A capacitive pressure sensor made of a foam spacer sandwiched between a conductive yarn and a common electrode [5, Fig. 2]. © 2010 IEEE

Figure 9. (a) Diagram of construction of a capacitive sensor belt for monitoring respiration. (b) Completed belt sensor. [31, Fig. 2.]. ©2013 IEEE

APPENDIX B

Data

Table 3. Spec sheets for fabrics in Groups 1-4.

Group 1 (polyester)						
Fabric #	thickness (microns)	pattern	count	weight (g/m^2)	Density (g/cm^3)	Air permeability (cfm)
4	489.0	weft jersey knit	28x26 (cxw)	160.0	0.3270	632.0
10	459.0	warp tricot knit	40x42 (cxw)	200.0	0.4430	269.0
12	478.0	plain weave	42x33 (wxf)	180.0	0.3790	121.0
19	465.0	twill weave	107x86 (wxf)	180.0	0.3940	8.930
Group 2 (polyester)						
Fabric #	thickness (microns)	pattern	count	weight (g/m^2)	Density (g/cm^3)	Air permeability (cfm)
9	249.0	warp tricot knit	42x35 (cxw)	80.00	0.3130	977.0
11	255.0	warp tricot knit	58x47 (cxw)	200.0	0.3940	541.0
18	216.0	plain weave	51x55 (wxf)	70.00	0.3370	908.0
Group 3 (nylon)						
Fabric #	thickness (microns)	pattern	count	weight (g/m^2)	Density (g/cm^3)	Air permeability (cfm)
13	152.0	twill weave	138x89 (wxf)	100.0	0.6350	6.570
24	191.0	plain weave	63x52 (wxf)	100.0	0.5320	26.50
Group 4 (acrylic)						
Fabric #	thickness (microns)	pattern	count	weight (g/m^2)	Density (g/cm^3)	Air permeability (cfm)
2	434.0	plain weave	48x40 (wxf)	140.0	0.3230	203.0
3	417.0	plain weave	50x40 (wxf)	150.0	0.3480	146.0
21	414.0	Crepe weave	75x60 (wxf)	120.0	0.2950	157.0

Table 4. Sensitivity for fabrics in Groups 1-4 at 0.479kPa and 3.83kPa.

Group 1			Group 2			Group 3			Group 4		
fabric #	0.479kPa	3.83kPa	fabric #	0.479kPa	3.83kPa	fabric #	0.479kPa	3.83kPa	fabric #	0.479kPa	3.83kPa
4	0.587	0.0900	9	0.203	0.0590	13	0.223	0.100	2	0.517	0.0570
10	0.211	0.0470	11	0.182	0.0530	24	0.194	0.0980	3	0.465	0.0550
12	0.345	0.0470	18	0.237	0.0660				21	0.272	0.0490
19	0.187	0.0430									

Figure 10. Graph of sensitivity for fabrics in Group 2.

Figure 11. Graph of sensitivity for fabrics in Group 3.

Figure 12. Graph of sensitivity for fabrics in Group 4.

Table 5. Linearity error for fabrics in Groups 1-4 at ranges of 0-0.958kPa and 1.44-3.83kPa

Group 1			Group 2		
Fabric #	0-0.958kPa	1.44-3.83kPa	Fabric #	0-0.958kPa	1.44-3.83kPa
4	6.00%	3.71%	9	5.00%	4.40%
10	8.19%	3.87%	11	4.27%	6.00%
12	11.0%	7.64%	18	5.11%	5.66%
19	4.79%	4.63%	Group 4		
Group 3			Fabric #	0-0.958kPa	1.44-3.83kPa
Fabric #	0-0.958kPa	1.44-3.83kPa	2	12.3%	4.92%
13	4.44%	3.44%	3	13.3%	4.38%
24	3.50%	2.19%	21	9.19%	5.46%

Figure 13. Graph of linearity for fabrics in Group 1 (0-0.958kPa).

Figure 14. Graph of linearity for fabrics in Group 1 (1.44-3.83kPa).

Figure 15. Graph of linearity for fabrics in Group 2 (0-0.958kPa).

Figure 16. Graph of linearity for fabrics in Group 2 (1.44-3.83kPa).

Figure 17. Graph of linearity for fabrics in Group 3 (0-0.958kPa).

Figure 18. Graph of linearity for fabrics in Group 3 (1.44-3.83kPa).

Figure 19. Graph of linearity for fabrics in Group 4 (0-0.958kPa).

Figure 20. Graph of linearity for fabrics in Group 4 (1.44-3.83kPa).

Table 6. Hysteresis error for fabrics in Groups 1-4.

Group 1		Group 2		Group 3		Group 4	
Fabric	Hysteresis error	Fabric	Hysteresis error	Fabric	Hysteresis error	Fabric	Hysteresis error
4	18.4%	9	10.0%	13	7.70%	2	18.5%
10	10.0%	11	7.80%	24	7.10%	3	19.0%
12	19.5%	18	7.60%			21	16.1%
19	16.2%						

Figure 21. Graph of hysteresis error for fabrics in Group 2.

Figure 22. Graph of hysteresis error for fabrics in Group 3.

Figure 23. Graph of hysteresis error for fabrics in Group 4.

Table 7. Repeatability of fabrics in Groups 1-4.

Group 1		Group 2		Group 3		Group 4	
Fabric #	SD mean (pF)	Fabric #	SD mean (pF)	Fabric #	SD mean (pF)	Fabric #	SD mean (pF)
4	13.6	9	3.18	13	8.27	2	4.86
10	1.96	11	2.52	24	14.6	3	7.31
12	4.31	18	7.39			21	2.71
19	2.73						

Figure 24. Repeatability of fabrics in Group 1.

Figure 25. Repeatability of fabrics in Group 2.

Figure 26. Repeatability of fabrics in Group 4.

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