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Fabric Sensors – Modelling Deformation in Knitted Fabrics

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Abstract. Fabric sensors are made from knitted conductive yarn and can be used to measure extension in wearable technologies and composite structures. Wearable technologies have considerable potential in sport and medical applications, for example recording limb movement in injury monitoring or sporting technique analysis.

The electrical resistance through the fabric varies with extension due to the change in contact area and contact force between yarns. The resistance can be interpreted using correlations with displacement to calculate the deformation experienced by the fabric sensor.

This paper describes a study which works towards a realistic digital model of a single jersey knitted fabric sensor by considering a non-idealised monofilament yarn of varied cross-section in a dense knit geometry. Models are created using TexGen, software developed at the University of Nottingham, taking advantage of its facility to create complex cross-sections which vary along the length of the yarn. Subsequent finite element analysis using ABAQUS with small representative volume elements and periodic boundary conditions showed high peak stresses at the boundaries, possibly caused by the contact surface being split across the boundary. Subsequent simulations using larger numbers of stitches and with relaxed boundary conditions in the x-direction showed more realistic deformations including reduction in width and curling of the material, reducing the impact of the boundaries on the overall fabric simulation, but with significant computational cost. The results give an initial assessment of deformations and contact pressures, which will aid understanding of the non-linear response found in mechanical testing and improve knowledge of how the inter-yarn contact varies. This work lays the foundation for further work which will aim to improve the similarity between the digital knit geometry and the physical sample, model larger areas of knitted fabric, include residual stresses from manufacture and use a multifilament yarn model. Subsequently the much more complex knitting patterns produced by the manufacturer of these sensors will then be able to be modelled.

Keywords: Fabric sensor, knitted textile, geometric model, finite element analysis

1. Introduction

Fabric sensors are used to measure extension and contact pressures in wearable technologies and composite structures such as aircraft or wind turbines. A wide variety of technologies are being developed, ranging from the addition of electronic components to the surface of a textile to the incorporation of the sensing material into the fabric of the device. In this study the fabric sensors are made from knitted conductive yarn where conducting steel fibre is spun into the yarn before it is knitted into the final article. The electrical resistance varies due to the change in contact area and force between yarns when the fabric deforms.

In order to use these materials as sensors for monitoring human body movements it is important to understand how the electrical response varies with elongation and movement, and particularly how this is affected by repetition of movement. Experimental work has been undertaken [1] to understand the effect of repeated extension on the behaviour of knitted materials in order to replicate extensions and deformations experienced by fabrics, for example deformations in a wearable sensor around the knee joint during walking, and the effect on electrical response of the material. In that work, four different knit patterns of varying complexity produced by Footfalls and Heartbeats (UK) Limited were examined.

This paper describes the initial step towards modelling of the response of these materials by modelling the deformation of fabrics. An accurate geometric model of the simplest of the four patterns, a single jersey knit, is developed using the open source textile modelling software, TexGen[2, 3], developed at the University of Nottingham. A previous study uses TexGen to model a similar, but idealised, knitted architecture [4], whereas the current study uses the facility within TexGen to create complex cross-sections which vary along the length of the yarn, thus creating a more realistic textile model.

2. Material and Geometry

The sample being modelled is a single jersey knitted fabric provided by Footfalls & Heartbeats (UK) Limited, the simplest of the fabrics used in [1]. The conductive yarn used in the fabric is a spun staple fibre yarn (Choeller, Bregenz,metric number Nm-50/2) constructed of 20% Inox steel fibre AISI 316L (conductivity 1.351 x 10^6 S/m, 8µm diameter) and 80% polyester (PES) low pill fibre (16µm diameter). The fibres were co-mingled when spun into a yarn.

Measurements were taken of the yarn diameter and geometry of the single jersey knit using an optical microscope as shown in Figure 1. Several measurements were taken for each parameter and the final values used for generating the model are given in Table 1.

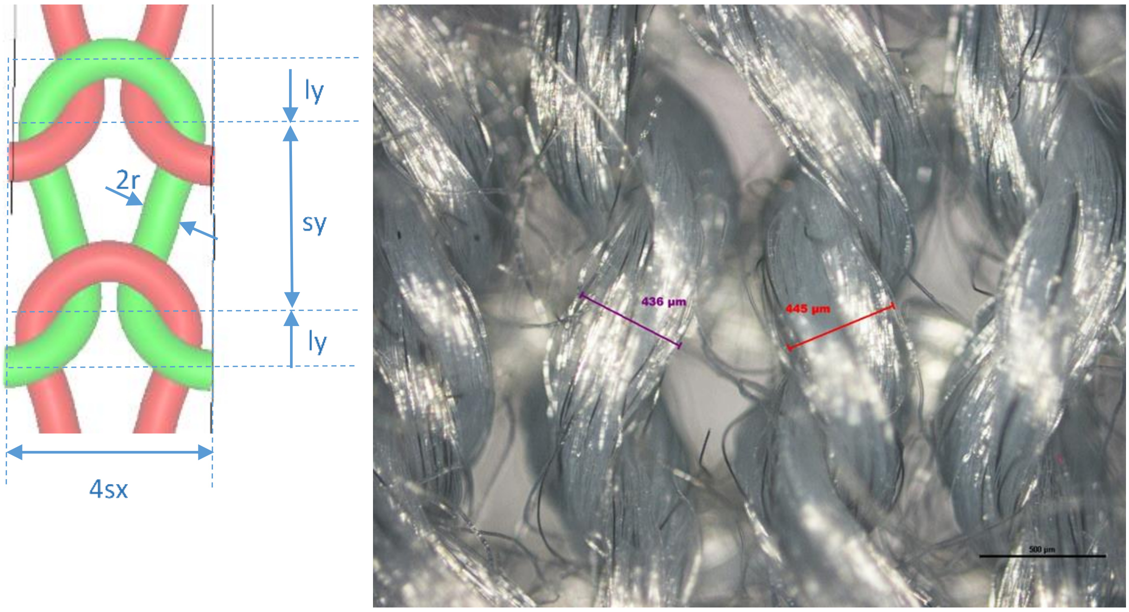

Fig 1: Diagrammatic view of measured yarn parameters (left), Example measurement – yarn diameter (right)

Table 1: Parameters used for generation of TexGen model

Parameter	Measurement /µm
Radius, r	216
Height, ly	363
Height, sy	1107
Width, sx	406

3. TexGen Model

TexGen software has been designed to give flexibility so that a wide range of textile models can be produced. The textile structure is built from yarns which are specified by a yarn path and cross-sections along that path. The yarn path is modelled by specifying its centreline, consisting of a series of nodes which give the smallest repeatable section of the yarn. An interpolation function then gives the exact path between the nodes. The yarn cross-section is then defined as the 2D shape of the yarn when cut by a plane perpendicular to the yarn path tangent. A complete description of the modelling process is given in [2].

Textile models can be generated either in the TexGen GUI or using the Python scripting API. The scripting method generally gives more flexibility for complex geometries and is the method used in this work. A generic Python script for a weft knit fabric was created by Sherburn [5] and is available to download from Github [6]. Modification of the script to use the values in Table 1 results in the model shown in Figure 2.

This model assumes that yarns have a constant circular cross-section and creates a model with 246 intersections between yarns over a unit cell with maximum intersection depth of 0.1mm.

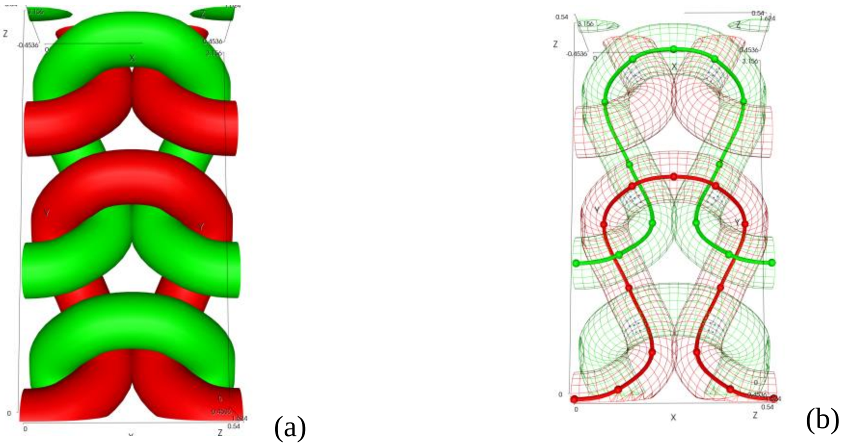

Figure 2: (a) TexGen model created using actual textile measurements with constant, circular cross-sections , (b) showing nodes, yarn paths and intersections

3.1. Reduction of Intersections in the Model

Several automatic methods have been proposed for the creation of textile models without intersections [7, 8]. In this case the approach taken is to use the functionality within TexGen to change the cross-sections at the yarn nodes closest to the positions with significant intersections.

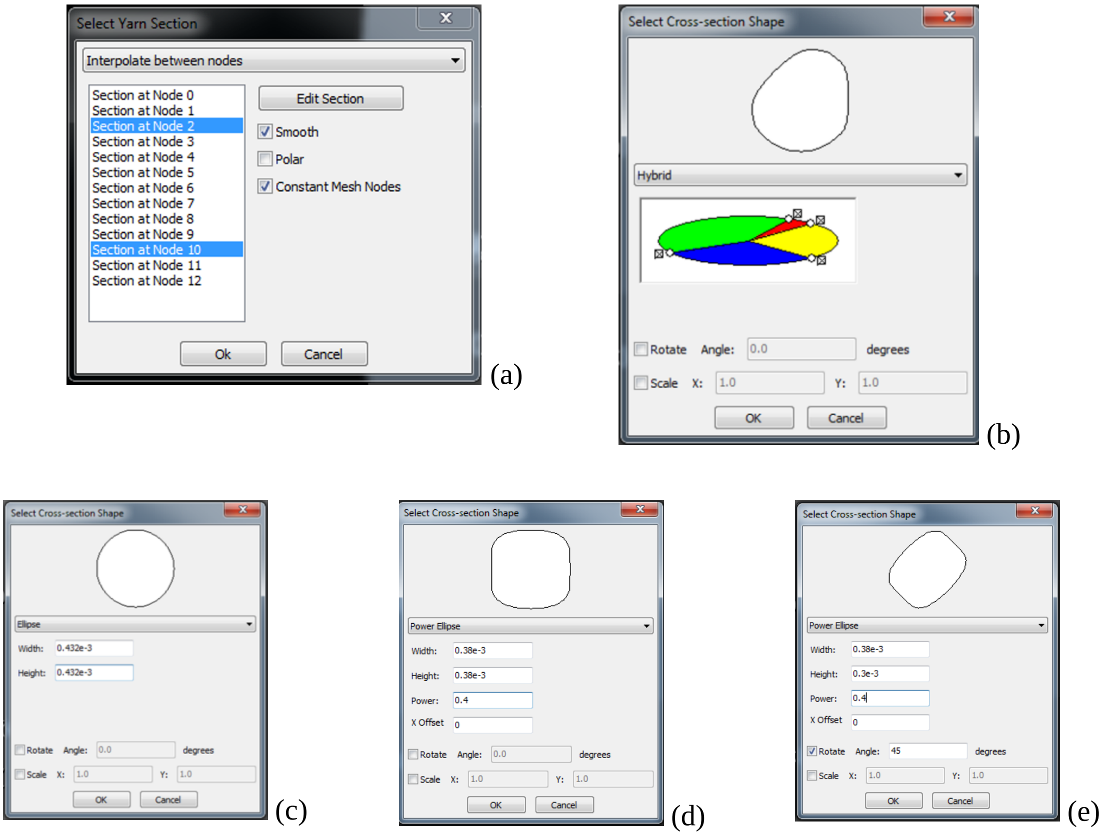

Figure 3: Hybrid cross-section: (a) Selection of nodes at which cross-section applies, (b) Allocation of shapes for the section, (c) Blue and red sections, (d) Yellow section, (e) Green section

Several options are available in TexGen for specifying the positions at which cross-sections of yarns are defined:

- Constant along entire yarn
- Cross-sections defined for each node in the yarn

- Cross-sections defined at user-specified distances along the yarn

In this case the cross-sections are defined at the nodes with three different hybrid sections being defined as well as the initial circular cross-section. An example of one of the hybrid sections with its constituent makeup is shown in Figure 3.

A domain is specified to define the section of the model to be considered, in this case forming a single unit cell as illustrated in Figure 4. The resulting model has no intersections.

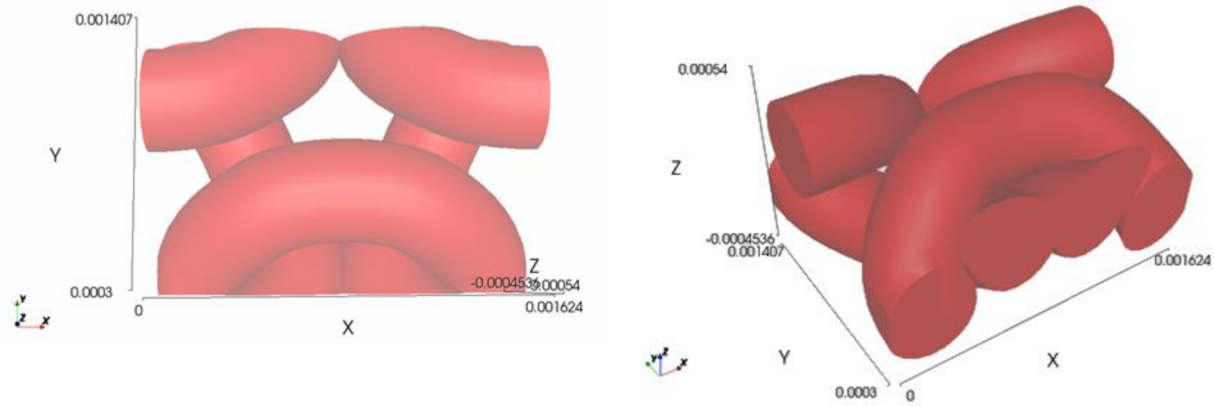

Figure 4: Single unit cell model with adjusted cross-sections

3.2. Material Properties

The actual material used for the knitted textile is described in Section 2. For the preliminary study reported here it was decided to use a monofilament, homogeneous material therefore providing significant computational savings and believed to be an acceptable approximation for initial proof of concept. The value of Young's modulus and Poisson's ratio were taken from Zeng [9]. The coefficient of friction used is the average static value for Polyethersoulfone (PES), grade count 14, as given by http://www.matweb.com/search/datasheettext.aspx?matguid=6be926d8eb0842abbfb80b5658ade95a . The properties used are given in Table 2.

Table 2: Material properties

Parameter	**Value**
Young's modulus, E	$3 \times 10^9 Pa$
Poisson's ratio, ν	0.3
Density, ρ	$1.637\ kg/m^3$
Coefficient of friction, μ	0.366

4. Simulation of Textile Deformation

The TexGen model is automatically exported as a conformal mesh in ABAQUS input file format using the ABAQUS Dry Fibre File export option. An ABAQUS/Explicit simulation is chosen due to previously reported problems with convergence of complex geometries with contacts when using static stress analysis procedure in ABAQUS/Standard [9].

The conformal mesh created by generating 2D meshes from the yarn cross-sections as shown in Figure 5a. These are then linked together to form 6 noded wedge and 8 noded hexahedral elements, Figure 5b. The resolution of this mesh is governed by the number of points around the cross-section.

In higher resolution meshes failure of the simulation was caused by the relation between element size and wave propagation. In some cases this was resolved by the removal of the wedge elements, achieved by removing the triangular elements at the corners of the 2D meshes. The simplest way to achieve this is by editing the TexGen .tg3 file and setting TriangleCorners = 0.

Figure 5: Conformal mesh generation, (a) 2D section mesh, (b) 2D meshes joined to form hexahedral and wedge elements

A mesh sensitivity study was carried out for a single unit cell, shown in Figure 6. A mesh size of 22 (the number of points around the cross-section edge) was selected, giving the best compromise between accuracy and computational time.

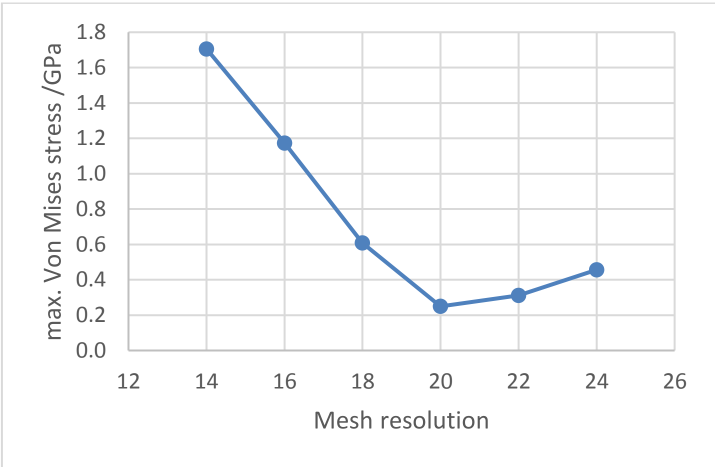

Figure 6: Mesh sensitivity study

4.1. Yarn Surface Contacts

There are complex interactions between yarns during deformation of a knitted structure and surface-to-surface contacts must be taken into account during any simulations. Code was developed which extended the current implementation of contact pairs in TexGen, originally defined for woven textiles which have an ‘upper’ and ‘lower’ surface which can then be defined as contact pairs in ABAQUS. This is not applicable to knitted textiles where the contact locations vary along the length of the yarn. The code was extended to output a single surface for the yarn which could then be used to define contact pairs.

An alternative method was to use the General Contact algorithm in ABAQUS where the contacts could be defined using the All Exterior keyword. It was found that this method was more computationally efficient for the models of knitted textiles.

4.2. Boundary Conditions

Initially periodic boundary conditions were applied to replicate the repeating nature of the knitted textile with the domain specifying one repeating unit of the fabric. In order to achieve this the displacements of neighbouring cells must be continuous and TexGen automatically sets up the nodal displacement difference constraint equations as given in equation 1.

$$\bar{u}^{j+} = \bar{u}^{j-} + \Delta\bar{R} \tag{1}$$

where $\bar{u}^{j+}$ and $\bar{u}^{j-}$ are the displacement vectors of matching nodes j^+ and j^- on opposite sides of the unit cell. $\Delta\bar{R}$ is the deformation vector of the unit cell. The ABAQUS input file automatically generated by TexGen implements these as an equation representing the relative displacement of the two node sets at opposite boundaries equal to the displacement of a dummy node. The unit cell deformation, specified from the TexGen interface, is then controlled by applying boundary conditions to the dummy node. In the simulations reported here the deformations were set to be 20% in the y direction.

Later simulations relaxed the constraint in the x-direction giving a setup which better represented the experiment. Here the fabric was subjected to an extension in one direction with one end secured and without constraint along the side edges.

5. Results and Future Work

Initial simulations using the periodic boundary conditions described in Section 4.2 showed maximum Von Mises stresses at the contact points on the boundaries as shown in Figure 7.Simulations with 2x2 unit cells showed reduced stresses at the contact points, implying that the boundary conditions affect the results.

Subsequent simulations with larger numbers of repeats showed more uniform stresses at the contact points across the textile. Relaxation of the boundary conditions on the boundaries along the y axis allowed movement in the x-direction and a more realistic representation of the deformation of the textile when a force is applied in the y direction (Figure 8). In larger models curling at the edges of the fabric can clearly be seen, in line with actual behaviour of knitted textiles. Contact pressures can be observed by removing one of the yarns from the view (Figure 9). This information will be of interest for future developments where the contact pressure and area of contact may be related to the conductivity of the fabric.

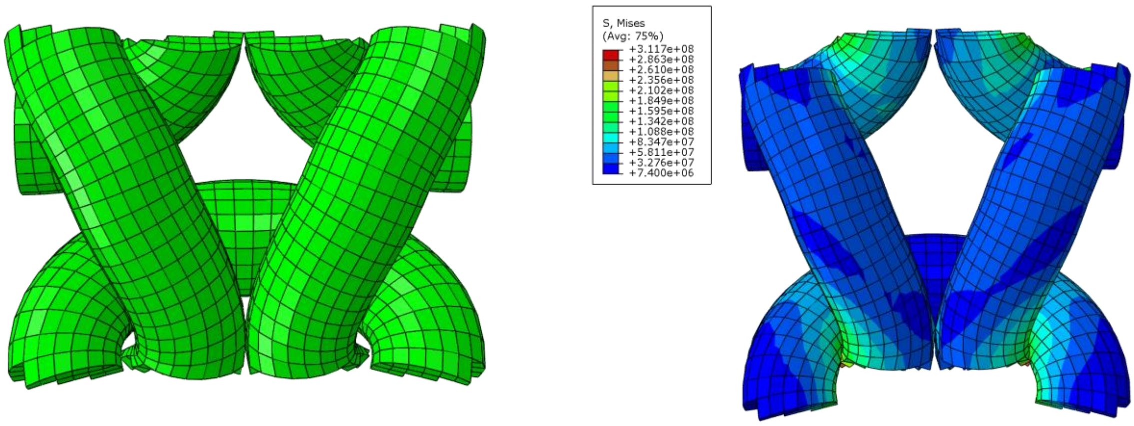

Figure 7: Unit cell in undeformed state (left), deformed (right)

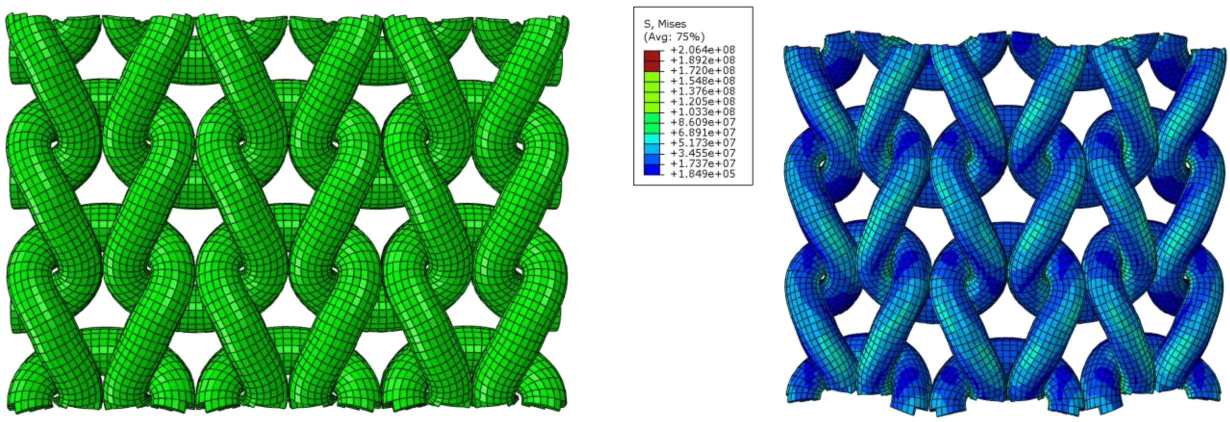

Figure 8: 3x3 unit cells, unconstrained in the x direction. Undeformed (left), deformed (right)

Ongoing work will validate simulation results against experimental results using samples manufactured from monofilament yarn. This will form the basis for work to create models of the more complex fabrics produced by Footfalls and Heartbeats and for better representation of the multifilament yarns. From this a method of relating the contact pressures in the model to the conductive behaviour of the fabric can be established.

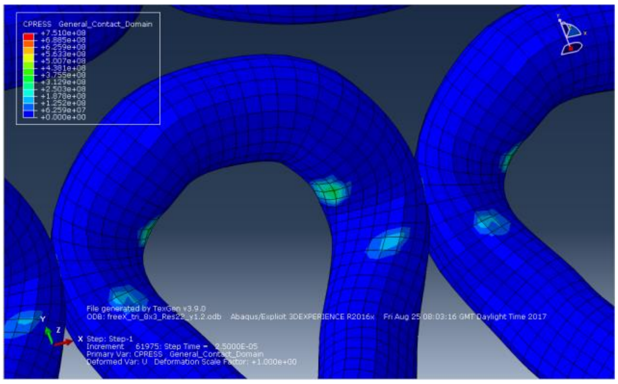

Figure 9: Contact pressures

6. Acknowledgements

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7. References

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