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To cite this article: R Guglielmini *et al* 2022 *IOP Conf. Ser.: Mater. Sci. Eng.* **1214** 012033

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The contact problem in FEM analysis of filiform structure for large deployable reflectors

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Abstract. Space reflectors need a continuous increase of size to improve the quality of the communication. Considering the small space available in launchers, the antenna must be assembled within the vector and deployed in the space environment. The antenna requires a thin metallic mesh sustained by an appropriate net structure. The best reflector efficiency is reached when all the metallic wires keep in stable contact, allowing the electrical field to be homogeneous. The number of wires involved is enormous, so that, the modelling requires a simple structural approach connected to a reliable contact tool. Single wires can be modelled by beams, but this opens a non-trivial contact managing. As a matter of fact, the wires describe a thin surface, but the contact is realized by 3D crossing. This point is the main objective of the present work which suggests a way to overcome the crossing while maintaining the structure modelling in a 2D field. The contact efficiency needs that the wires do not exceed the elastic strength, causing a lowering of loading contacts due to irreversible deformations. Taking advantage of the present approach, an investigation over the percentage of active contacts in a full mesh is performed, so that optimally applied tensile loads are identified.

1. Introduction

The capability to communicate using a satellite connection is strongly linked to the quality of the signal. Satellites receive and send messages overtaking any obstacles thanks to their high altitude in the atmosphere. They operate in a specific orbit that has itself an area of service on the earth called footprint, generally variable in time. For receiving a message, the satellite must reflect it on a single point, the fulcrum of the parabolical structure, by means of a reflector, also called LDR (Large Deployable Reflector). To optimize the number of bits correctly read by the satellite, the reflector requires particular attention to the metal mesh regularity. LDR contains several knitted thin wires in order to minimize the cost of the entire mission reducing the weight of materials carried in orbit.

Research on reducing costs in the aerospace field has shifted to the development of structures with customizable functions that can provide enhanced functions for smart products [1]. The technological process of textile manufacturing offers the potential to produce a new generation of material systems that extends traditional textile applications [1], [3], [4]. Due to the particularity of fabrics and the complex relationship between stress and deformation, the mechanics of textiles makes the modelling of

these structures quite tricky [5]. There are three main types of textile fabrics: woven, knitted and non-woven fabrics [4], [6]. The most commonly used configuration sets are described in detail in [7]. The stitches of the knitted fabric are arranged in rows and columns, roughly equivalent to the warp and weft directions of woven structures. Knitted fabrics have some advantages over woven and non-woven fabrics: they have higher elongation, so they allow the production of "flexible fabrics" with a wider range of available deformations [8]. This statement is particularly meaningful and focuses attention on knitted mesh structures, the characteristics of which can be planned and calibrated in advance to achieve the desired effects.

The first attempts to gain a mechanical model and analysis of textile structures began about a hundred years ago. The first publication appeared in a report by R. Haas in the National Advisory Committee for the US Air Force in 1918 [9]. This article discusses theoretical and practical aspects, as well as possible tests and applications. However, Haas's work has been unknown for a long time, and Pierce's work [10] is considered the starting point for mechanical modelling of textile structures. Since then, researchers have begun to work on the application of existing analysis methods, used in other engineering fields. In aerospace applications, knitted fabrics have become essential for constructing reflectors for deployable antennas used on communication satellites [11], [12].

(a)
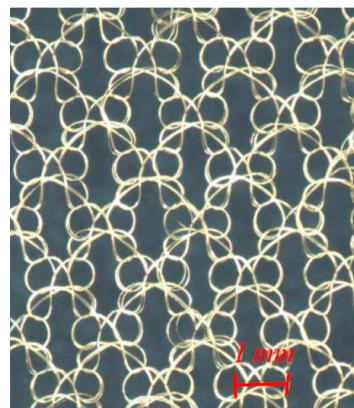
(b) **Figure 1**. **(a)** A satellite orbit around the Earth; **(b)** Knitted metallic mesh

Different aspects must be considered very carefully when designing the LDR; electromagnetics, structural, kinematics, dynamics and thermals, and technological limits must not be ignored. Most reflectors on orbit are made of strictly parabolic structures. The introduction of LDR supports the need to greatly increase the size of the reflection area and so the signal-to-noise ratio, while considering the reduction in the weight and cost of the transmitter. At present, the size of the reflector used is as large as 15 meters, but a larger diameter, such as 30 meters, is currently being developed [13], [14]. To achieve this dimensioning, the antennas must be equipped with a deployable mechanism to open in orbit. The parabolic surface reflects electromagnetic waves, and it is made of metal knitted fabric. The knitted fabric is sustained and fixed in position by a net that does not have any radio capability. Using these devices, satellites can benefit of a low weight structure [15]. The geometric accuracy and the compliance of the LDR must be accurately studied. Therefore, a structural analysis of the whole must consider the sustaining structure, the net where the metallic mesh is applied, and the metallic mesh itself.

The main difficulty in mesh characterization comes from the low overall stiffness associated with large displacements and slight loads: these features induce special attentions. For example, a basic aspect is the grasping system. If it is not optimized, it will introduce a local hardening effect, thereby changing the overall elasticity assessment [16]. Testing for structural characterization requires dedicated equipment. In [17], the experimental test was carried out using a customized two-axis electromechanical device. The testing machine is equipped with a clamping system to reduce the adverse effects just mentioned [18].

The mesh could be weaved in different ways, but it influences the SNR (Signal Noise Ratio). The best solution is to have a warp knitted reflector with Atlas-Atlas stitches. Voids make structure lighter

but can negatively affect the reception of the signal: if the void dimension is bigger than ten times the wavelength of the signal, the antenna cannot reflect the signal. A good match of the different wires is realized if the mutual contact keeps stable and this condition makes the almost isotropic movement of electric charges all around the net. The number of the active contacts is although governed by the boundary conditions applied at the mesh, i.e., the tensile loads applied while connecting the mesh to the net during the building phase on earth. An optimal service configuration that guarantees the maximum number of contacts is performed, considering the stiffness of all components forming the reflector and assembling a model to study by Finite Element Analysis. The critical point is that the contact must remain active also when the satellite travels on a shadow area, and the structure is subjected to contraction, or when it is totally exposed to the sun radiation, suffering dilatation [19]. These combined effects cause to withstand a large temperature variation, from *-190°C* to *+140°C* [20]. The metal wire is usually made of molybdenum or tungsten, covered with gold, and its diameter is very thin (approximately *15 microns*), compared to the diameter of the loops (few millimetres).

The enormous computing power available nowadays allows the development of commercial computation codes with advanced mechanical analysis capabilities and it promotes the adoption of numerical methods by textile designers. Finite Element software provides different strategies to be used to correctly model knitted fabrics. Explicit FEM can be used to simulate small or large deformed meshes in static or dynamic analysis [21]. Implicit FEM is more effective for small deformations. The software allows the adoption of different element types to model different geometric shapes: generally, beam elements are used for yarn modelling, even if solid and shell element discretization is also recurrent. [22], [23]. In one-dimensional modelling, each wire is discretized with a simple beam, rod, or spring element. The knitting produces a basic pattern that repeats periodically to form the entire mesh [24], [25], [26]. Difficulties arise because in Finite Element codes, the identification of contact between objects is usually one of the most time-consuming operations [27], and the number of wires in contact is in the order of millions per square meter, very hard to manage. For this reason, only a very limited fabric portion has been modelled so far [28], [29]. Contact problems introduce strong nonlinearity that affects convergence [30]. The whole reflector, knitted by several wires, can be easily modelled in a 3D representation using CAD software; but the attempt to solve the mesh structure by modelling all curved wires through beams introduces a huge amount of elements and elements-in-contact, that makes the computation lengthy and convergence is hard to achieve.

The authors [31] are developing a new 2D technique to model the wires with a limited number of *DoFs* and a simplified contact algorithm; but there is the exigence to validate the approach through a Finite Element Analysis, that is performed in the present paper.

In the simulations reported below, a 2D modelling is preferred, that, however, induces some problems to manage the contact. Hereinafter some different approaches are taken in exam to identify the most profitable technique for contact.

2. Method

Using the classical features and the element in the library of Finite Element codes, a 3D modelling of the reflectors should be the best choice. However, this approach requires too much *DoFs* and the solution provides a long computation time and convergence difficulties.

As it is clear in figure 2, the crossing among wires realizes out of the mesh plane. Although, the diameter of the wires is so small, compared to the loops, that it seems very reasonable to condense the overlapping 3D contact into a 2D action largely reducing the contact complexity.

In such 2D representation, a couple of wires crosses in two points, if these keep distance the contact is non-active, when they tend to approach, so close as *1.25* times the diameter, the contact activates. Another aspect regards the considerable reciprocal sliding, the contact region may move while loading so that the a-priori paring of the elements in possible contact, necessary for the modelling, turns troublesome. A good idea to represent the 3D contact through a 2D modelling is to interpose a spot element within the interlaced loops, which is free to move in plane, but is potential contact with both wires. However, as the previous definition suggests, it has free rigid motions, and the solution is

therefore impossible using static analysis (if some part of the model is free to move the stiffness matrix $[K]$ becomes singular and the elastic problem $[K]\{x\} = \{F\}$ has no solution). To provide a static solution, one must apply some constraints at all contact spots, but this may affect the overall behaviour of the mesh.

Keeping within static analysis, the problem with this element could be solved through three different strategies. All of them introduces additional elements providing contact that are restrained in some way to prevent the lability of the model. Generally, this is obtained by introducing dummy springs that require energy to move or by adding dummy friction on the plane where movement is possible.
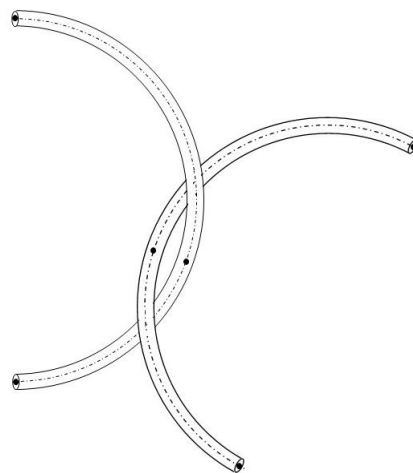

Figure 2. 3D crossing between wires.

An interesting alternative is made possible if a dynamic analysis is conceived, in fact, any lability is overcome since inertia loads are always connected to movements. This option is also investigated, considering that the structure requires the modelling of two features: stiffness and inertia matrices.

2.1. Single contact point
For this research, we referred to a commercial Finite Element Code, ANSYS®, that provides several algorithms for non-linear contact features. The procedure introduces a relationship between *DoFs* of elements not structurally connected before contact. The technique follows two alternative approaches (or mixes them) known as Lagrange multiplier or Penalty mode. Whatever is the method, the different algorithm is to be chosen in a group of elements that share all the information to define contact features. These elements are classified in two families: contact and target elements. Generally, contact and targets are defined over an extended region that considers both parts that might come into contact. This is difficult to implement when 2D analysis is performed. In fact, the two overlaps (see figure 2) are misinterpreted as contact even if they are not close. The way to overcome this difficulty is to limit the contact region, of only one of the wires, to a simple spot. However, this position only works if one is aware of the effective location of the contact, even when some sliding occurs. This is generally not known a-priori. An example is represented in figure 3 where two wires knot themselves in the middle with particular boundary conditions: inferior ends are totally constrained, while superior edges are respectively free to move in vertical direction and in both vertical and horizontal one, with an imposed displacement in the last. Wires have a circular section of *15 μm* and a curvature of *1 mm*. It is interesting to highlight how it is difficult to locate the contact point in the undeformed configuration. This is troublesome for two wires, for an assemblage of several wires this prediction is almost impossible. Moreover, the contact spot may also skip the target region and the contact is missed, eliminating the physical crossing action.

The Analysis considers three nodes beam element BEAM189 [32], one contact element CONTA175 in the left wire, and target elements TARGE170 with cylinder shape, all over the right wire. Hereinafter the material considered is tungsten (W) with a density of *19250 kg/m³* and Young's modulus assumed *400 GPa*.
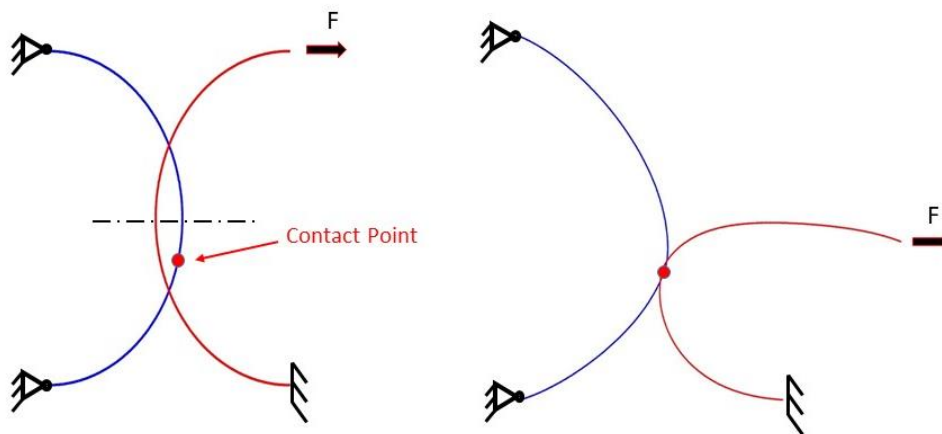

Figure 3. Contact of two 2D wires with a single contact point vs target.

In order to consider the thickness of the beam in contact is possible to account for it using a contact offset (CNOF command [33]) accounting of the wire diameters. As an alternative, the shape of the elements going into contact can be defined through the command TSHAP that provides the shape of the target elements that remain rigid during the interaction. In this case, TSHAP is set as CYLI (cylindrical) fixing its value with the radius of the wire. As already said, in the evolution of the simulation the contact could slip away and nobody else contributes to keeping the two wires bonded. Furthermore, the contact spot remains fixed on one wire, but this could be far from reality because the sliding interests only one of the two wires.

2.2. Interposing a rigid body restrained by springs

An idea to afford this problem provides an external element connecting the two wires. This is free to move thanks to additional constraints. This element could be a single point or a cylinder inside the common region, or a ring (modelled through beams) embracing both wires (see figure 4).

| (a) | (b) | (c) |
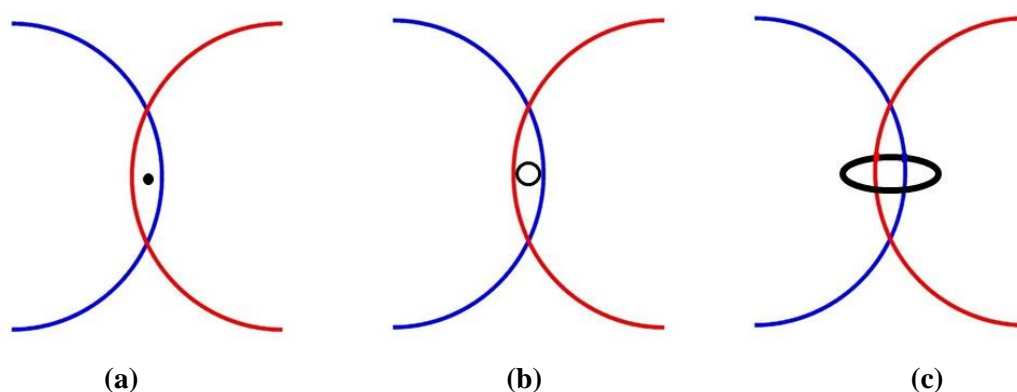
Figure 4. Three different external elements to model a 2D wires contact in 2D:
(a) single point; (b) cylinder; (c) ring.

To avoid the free movement of this interlacing element springs to the ground are added. It is not easy to find an optimal value for these external springs. Too high values cause the deformation to assume non-physical shapes, too low values cause difficulties in the convergence during large deformation analysis. For the analysis here considered the optimal stiffness value is close to *0.001 Nm*. But this value

is tuned for the two wires considered. For a larger wired structure, this value could not be suitable. The other solution regards a rigid ring embracing the two loops. External springs are also necessary to avoid lability. In this last case, the contact is no more a spot and is extended to the whole internal region of the ring.

All the proposed solution considered in this section allows the full sliding of both wires and the contact may be not fixed a-priori that was the pitfall of previous Single Contact Point approach.

Comparing the three solutions for contact here provided, it is clear that the simplest one, to obtain the sliding of the contact region, is to generate a single body in the between the two wires. However, the effect of the added external stiffness to the single point unpredictably affects the results.

2.3. Plane whit friction contact
As an alternative to the added springs, friction can be added to the single bodies introduced. A friction plane is introduced. This plane is bigger than the structures and is made from four-point linked in a quadrilateral element TARGE170 with TSHAPE, QUAD. Over that single point between the wires is then modelled another contact CONTA175 element. These two elements are then paired together thanks to a new real constant set dedicated to the couple. Although possible, this solution introduces additional difficulties in terms of non-linear effects. For the interaction of two wires it works, but for more complete knitted structures the difficulties increase exponentially.

2.4. Dynamic Analysis
Structure analyses within static conditions need a well-constrained and numerically stable model to achieve reasonable results. The wires are very thin with a low stiffness so that it is easy to incur bad-conditioning problems. In addition, the external springs or the friction constant used to stabilize the modelling must be appropriately chosen. If a dynamic simulation is assumed, there is the need to introduce masses at all *DoFs*, but lability is prevented by inertia loads always present during displacements. The mass values of the single bodies may be set in the order of less than half a loop of the wire. The evolution time chosen for the analysis assumes a significant value and, in connection with the masses is chosen so that almost no vibrations occur while applying loads. From the point of view of computing time, using lumped mass evaluation does not significantly change the overall values, but also smooths the convergence difficulties. Comparing to the added stiffness or friction plane approach for the static analysis, it is much easier to tune the single body masses so that their influence is minimal.

2.5. Modelling the LDR
Moving from a simple modelling consisting in two wires to the complex metallic mesh involves an exponential growth of the problem in term of computing time and contact analysis. In fact, the mesh is composed of a huge number of loops that knot together. Let us consider figure 5 representing a portion of fabric. This structure develops with 2 types of loops: a circular and an oval one that is mirrored and repeated (evidenced in red). Observing the mesh, these two loops along the longitudinal direction of weaving generate an essential structure that could be called "primary portion" (blue in figure 5). Adding a primary portion with a mirrored one, (violet in figure 5) the "elementary wire path" is completed and similarly, it repeats towards the warp direction.

From the point of view of FE analysis of the primary portion model is crucial to forming the entire structure. Using straight beams, no less than *400* nodes are necessary to get a reliable structural behaviour of the primary portion. This is mainly because of the contact identification and sliding. When several primary portions are present, a full mesh requires a massive number of *DoFs* that grow together with the size of the mesh. In addition, each circular loop can activate three contacts that, as described in paragraph *2.4*, require the insertion of contact bodies within the crossing region.

In order to reduce the computational cost a representative part is found observing the mesh, optimizing the power of the simulation and searching results in it: primary portion could be associated to a single edge, or element, that subsequently generate a structure made by rhombus. The rhombus

could be defined as "complete" when in every edge, all the contact points are potentially activated and they are enough far from external bound, so not affected by boundary conditions.
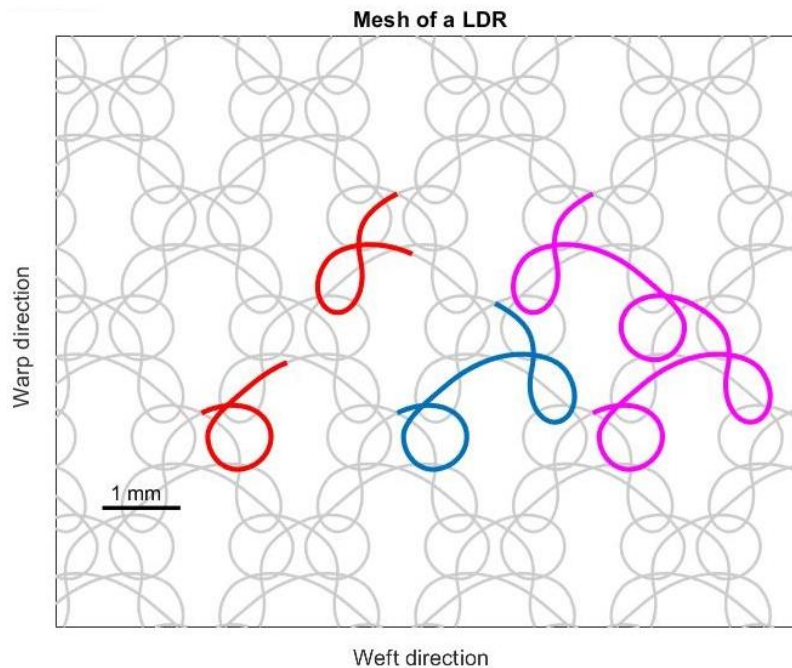
Figure 5. Description of the different portion in the mesh. From left to right: circular loop and oval one; 'primary part' and 'elementary wire path'.

The need to model a consistent portion of fabric to account of its structural response is given by the difficulty in applying boundary conditions. These are applied on the edges of each wire, but they introduce local disturbance that makes difficult this characterization. Therefore, the characterization is completed on the central rhombus (see figure 6) that is less affected by boundary loading.
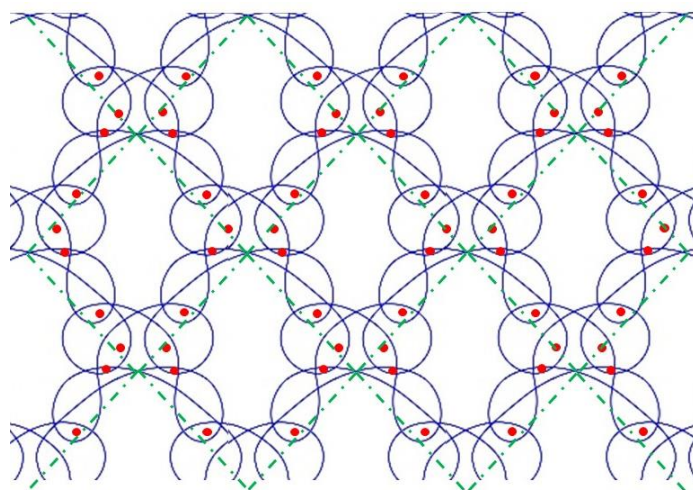
**Figure 6.** Location of the contact bodies and the repeated rhombus pattern.

3. Results

The primary goal is to investigate the number of active contacts under differing boundary conditions. As written before, a homogeneous distribution of electric charge in every load condition reduces SNR and improve the quality of data exchange. The percentage of active contacts is strongly related to initial boundary conditions and should be maximal to enhance the performance of the reflector. The model is so submitted to different load conditions and percentage of active contact is taken into account. One of

the modelled structure deformations is represented in figure 7 that refers to an isotropic displacement of *1.2 mm*.

The meaningful structure suggests investigating the status of contact bodies in the complete rhombus placed in the middle of the model. In the rhombus, there are 12 contact bodies for a total of 24 elements of contact (everyone describes the interference between two wires and needs two different contact pairing).
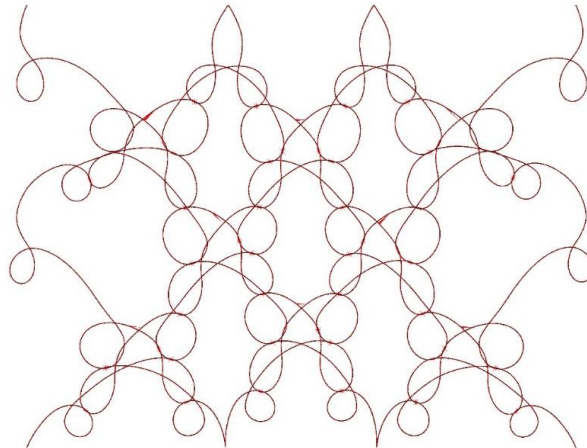
Figure 7. Deformed configuration of the mesh submitted to an imposed displacement at all boundaries both in warp and weft direction. Imposed displacement is of *1.2 mm*.
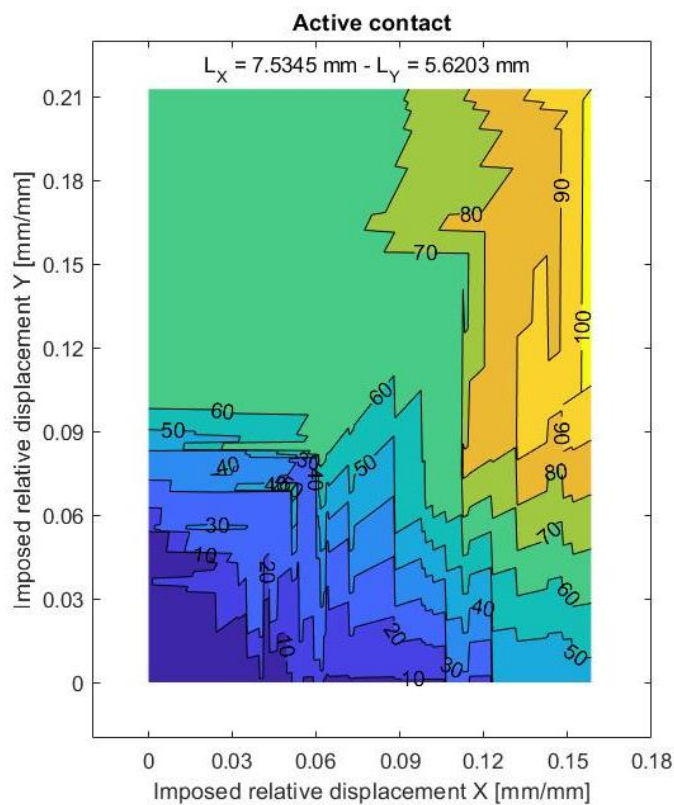
Figure 8. Contour map of percentage active contacts. The axes give the imposed deformations.

External loads are supplied by means of imposed displacements at the end of every wire. Figure 8 condense the results of many computations. It is evident that poor strains cause a low number of activated contacts. However, it is interesting to highlight the non-isotropic behaviour of contacts in the warp and weft directions. The warp direction (vertical in figure 8) is stiffer than the warp one. However, from the point of view of contacts, they need to activate a sufficient strain in the weft direction.

Deformations in the weft direction are, for this reason, crucial to optimize the behaviour, but a little change of them causes the loss of a huge number of contacts; on the opposite, the mesh in the weft direction is more stable from the point of view of activated contacts. Around a homogeneous 10% of deformation is necessary to activate a significant number of contacts for this Atlas-Atlas configuration. This result concerns this particular mesh and cannot be generalized. What is general is the method that applies to any other metal knitted mesh.

In correspondence of the 10% deformation, it was carried on a thermal verification of the contact stability. The results show that at the temperature changes considered (*-190°C* to *140 °C*) the percentage of contact keeps stable, so this is not a cause of malfunctioning of the reflecting mesh.

4. Conclusions

The present paper concerns the analysis of contacts of a metal mesh subjected to imposed deformations. The analysis is conducted on a specific knitted mesh, but the method has a general meaning. In the paper, FE analysis has been adopted to gain a reference for a more specific method developed by the authors. In fact, convergence difficulties make it difficult to analyse a full antenna mesh with commercial finite elements. Nevertheless, the finite element can be used when considering a small portion to achieve its characteristics in terms of stiffness and contact diffusion.

Among all possible techniques to manage the contact in a 2D frame, many of them have been reported in the paper. The resulting best way considers the insertion of a massive contact body and conducting the analysis in a dynamic contest. This allows to represent the contact, which is a physical 3D crossing of wires, as the coupling of two loops in a 2D reference. This method also allows the sliding of contact points which is determinant in the analysis of knitted metal meshes.

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