DIGITAL MODELING OF THE SURFACE OF THE DIAPHRAGM CIRCULAR LOAD CELL

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Abstract. *A graphic representation, as well as digital surfaces, is present in all areas. This representation goes by electronic games and reaches at the design of the more modern equipments, such as those for space travel, advertising, electronic devices, and medical equipments. In the last ones, the image of internal organs of the human body allows the diagnosis of illnesses that, in other times, it would only be possible with invasive, complicated and compromising procedures. Thus, the imaging and digital surface give support for new languages and forms of expression, encouraging experimentation of these offered possibilities, such as movement, interactivity, and computing. This work aims to analyze the type and model of the circular digital surface generated by the computer simulation using MATLAB software. It is given an overview of the modeling techniques applied in the areas of imaging, and its basic concepts. The work is also structured in specific case study allowing the analysis in which it is proposed. It can be concluded with this work that the imaging and digital surfaces have a strong interaction with calculation, geometric design and computer simulation*

Keywords: *graphical representation 1, digital surfaces 2, computer simulation 3*

1. INTRODUCTION

In the world industry current context, as an effect of globalization, we use of several computational techniques and methods in order to solve various engineering problems, as a good example the use of graphic computing. Graphic computing makes possible the visualization in (2D and 3D) of many problems such as engineering problems, in a quick practical and efficient way and the visualization of data through graphic means.

According to International Standards Organization – ISO – graphic computing can be defined as the set of methods and techniques used in order to convert data into a graphic device, via computer.

According to Pinho (2009) if we have as a basis the definition of ISO, two areas have a close relation to graphic computing: image processing and pattern recognition.

Pettinatti (1983) emphasizes that graphic computing is an area whose importance has been increasing every day, thanks to images and the graphic representation that it can produce.

Araujo (2003) emphasizes that the graphic representation of a surface on the computer is fundamental to the elaboration and creation of its digital modeling, which can be represented by analytical equations or point grid.

According to Itame (2001) digital modeling can be represented by a point grid (square, rectangular, triangular grid) that can be distributed in a random or organized way.

Pinho (2009) emphasizes that among the interface applications the user between the graphic representation and digital modeling we have: interactive tracing of graphics and visualization, electronic editing, CAD, computational simulation, animation, art and commerce, process control/visualization and cartography

In this context, MatLab is computational software that has been widely employed as a powerful tool for computational simulation and used in several tasks for simulation. Based on these presuppositions, the objective of this paper is to point out the model, the type of class and the representation of the circular surface of the diaphragm of the load cell, by computational simulation, by using MatLab.

2. STATE OF DIGITAL MODELING ART

Digital modeling is a mathematical representation of the spatial distribution and the characteristic of a phenomenon connected to a real surface. The surface is usually continuous and the phenomenon that it represents can be varied. For the representation of a real surface on the computer it is fundamental to the creation of a digital model, be it through analytical mathematical equations or through a point grid in the shape of a grid of regular and/or irregular points.

From the models we can calculate volumes, areas, draw profiles and transversal sections, generate images and 3D perspectives Felgueiras (1998).

In nearly all the sciences and fields of action of engineering there is the need to present surfaces through digital modeling of interest, analytical, through equations, or numerically, through a set of values sampled, so it is necessary to present them graphically, expressing its behavior with the shapes of curves or even perspectives Pettinatti (1983).

Whatever the surface, the process takes place from physical observations in order to determine the model so that it is analytically treated, reproducing the surface as well as possible. In the study of the behavior of the surfaces it is usually carried out through mathematical models Pettinatti (1983).

According to Pettinati (1983) the modeling process of a surface Fig. 1, by using the computer involves three steps: information collection; elaboration of a mathematical model; use of the model.

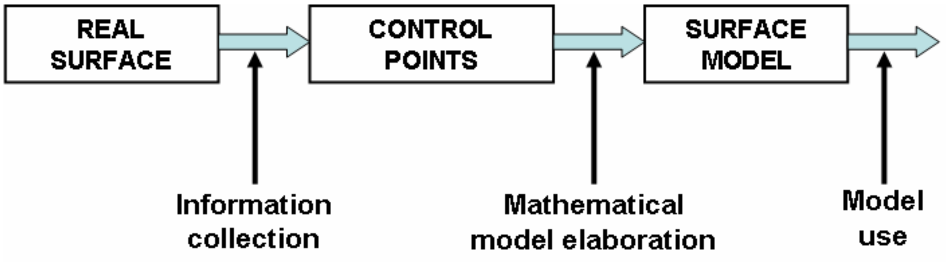
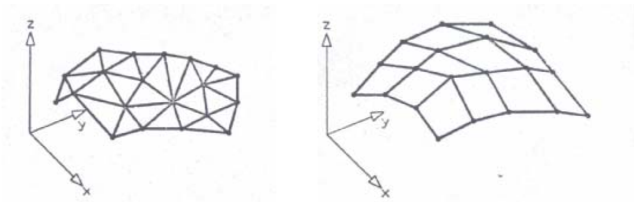


Figure 1. Modeling process of a surface Pettinati (1983)

The information collection consists in the sampling of a certain number of distributions of points on the surface in study, which are called control points. They can be regular or non regular. In the distribution of regular points the matrix shaped distribution rules and for the non regular distribution no laws of formation are applied, therefore, a less attentive observer would consider this distribution as random Pettinatti (1983).

According to Peucker *et al.* (1975); Toriaki *et al.* (1978) the regular distribution of points only occurs in the sampling process and it is completely random from the point of view of the surface structural characteristics.

According to the distribution of the control points, we can have different classes of polyhedrons, in case the sampling is carried out in a non regular way, the points will be put together, forming a triangular grid Fig. 2a, and if the sampling is regular the points will then be put together forming a rectangular grid Fib 2b Namikawa *et al.* (2003) Fig. 2.

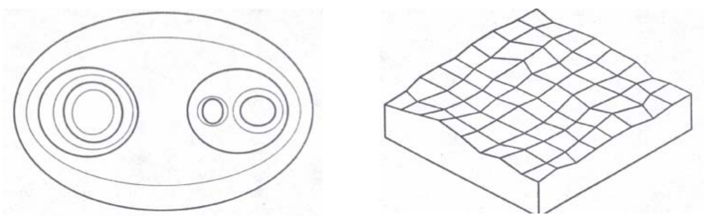


(a) Triangular grid (b) Rectangular grid

Figure 2. Different classes of models Namikawa *et al.* (2003)

With the two classes of models of distribution of points on the surface we have two usual types of graphic representations, the iso-value curves and the perspectives, which are presented on Fig. 3 Namikawa *et al.* (2003).

The iso-value curves are lines that connect points of the same height of the surface. The perspectives are obtained through drawing, in perspective, of the polyhedron that composes the model of the surface, although it is possible to represent it in perspective not only composed models by polyhedron of triangular faces but also rectangular ones.



(a) Iso-value curves (b) Perspective

Figure 3. Graphic representation with iso-value curves and perspectives Namikawa *et al.* (2003)

2.1. Model construction

Modeling involves the creation of data structures, definition of adjustment surfaces for the elements of those structures. Obtaining a function defined in the study region can be a global or local method.

The global models are represented by a function defined, by using all the elements of the set of samples. The local models use functions whose coefficients are defined by sampling elements chosen inside of local region of interest.

In the construction of surface digital models we need to start the sampling process of control points by surface on the surface of study. Considering that the distribution of control points is irregular we proceed the construction of model with triangular grid, or rectangular grid or both grids at the same time, directly from the control points.

The triangular grid is a digital model that approximates surfaces through a polyhedron of triangular faces, the vertices of these triangles are control points previously sampled denominated triangulation.

The rectangular grid is a model that approximates surfaces through a polyhedron of rectangular faces. The apexes of these can be either control points, in case they have been sampled in a regular way, or obtained through interpolation procedure, in case the points have been sampled in a non regular way Namikawa *et al.* (2003).

One of the most important aspects of the rectangular grid is the necessary care in order to determine the horizontal and vertical spacing of its elements. The reason to justify the preference for the rectangular grid over the triangulation is because it is the oldest way and that consequently was implemented before. The usual routine is to use the rectangular grid, as for the graphic representation production aspects, in function of the better aesthetical quality that it provides to the drawings. Depending on the type of graphic representation we can use the method that better adapts to the situation.

The surface modeling does not finish after the construction of a polyhedral model, the triangulation and the rectangular grid must come along with adequate interpolation functions – interpolating.

The triangular and rectangular grids are obtained by spatial interpolation from a data sample. Spatial interpolation is a procedure that has as a goal to estimate values of unknown points from known points, inside an previously determined area. We understand "point" as a geometric measure identified by its coordinates, within a perfectly defined Cartesian system Coelho (2006).

Criteria definitions, conceptions and applications can be consulted with more details in Namikawa *et al.* (2003), Pettinati (1983), Coelho (2006) and Carmo (2009).

2.2. Tracing and graphic representations

The graphic representation trace is carried out by drawing the elements that constitute the digital model of a surface or other elements that derive from it. The graphic representations are grouped into two distinct classes, the quantitative character ones, that allow us to carry out measurements directly on the drawing (iso-value curves) and the qualitative character ones, that provide an indication of the behavior of the surface (perspectives).

The iso-value, are curves that gather among themselves all the points of a surface that have the same height, denominated level curves, projected on the XY plane and on the intersections between the surface and a family of horizontal equidistant planes. Fig. 4a presents the iso-value curve model Pettinati (1983).

(a) (b)

Figure 4. Iso-value curve model and representation in perspective Pettinati (1983)

All iso-value curves are closed, except from curves that intercept the border of the interest region. The important property of the iso-value curve is about the fact that they never cross with each other due to the interpolation method that approximates the surfaces Namikawa *et al.* (2003).

In a drawing containing iso-value curves, information of quantitative character is provided. The inclination measure or even the calculation of the areas and volume can be carried out directly and in a fast and sufficiently precise way Namikawa *et al.* (2003), Pettinati (1983), Coelho (2006), Itame (2001).

The trace of the set of iso-value curves of a surface can be carried out in an automatic way, from either a triangulation or from a rectangular grid. Two methods are basically used Namikawa *et al.* (2003), Pettinati (1983): the tracking method and the cell method.

Comparisons of the methods, visualizations of the intersections, behaviors of the safe iso-value, subdivision of the cells of a digital model and effects of the iso-value curve aesthetics, please consult Namikawa *et al.* (2003).

The representations in perspective consist in the projection in perspective of the polyhedron that constitutes the digital model of a surface. The perspectives contain only information of qualitative nature although they do not allow the measures of direct calculations, the perspectives produce a more loyal representation of the surface Fig. 4b.

For the representation in perspective produced by the model of a surface it is necessary to map each point of each edge of the model for a drawing plan. The mapping is carried out through functions of plane projection determining the intersection between the set of lines denominated projecting lines, passing by each point of the model and a projection plan Namikawa *et al.* (2003).

The projecting lines emanate from a unique point known with projection center coinciding in which the observer that is looking at the surface projects it. When the projection center is at a finite distance from the surface, the projecting lines are not parallel and the projection obtained is denominated perspective or conic projection. When the projection center is infinite, the projecting lines are parallel and the projection obtained is denominated parallel or cylindrical Pettinati (1983).

Eventual problems that might occur when determining the visibility and invisibility occur when there is a discontinuity on the surface or when the observation point is at a short distance from the model Anderson (1982).

The solution of the problem implies determining which edges are visible and invisible, considering that the problem of invisibility is solved through the class of methods known as hidden line algorithms. Studies of this application can be found in Namikawa *et al.* (2003), Pettinati (1983).

3. SURFACE COMPUTATIONAL SIMULATION

The surface computational simulation is nowadays present in all the sciences and areas of knowledge and its importance tends to increase. It is the way to confront theories with experimentation, anticipate experimental results or performing experiments that would be inaccessible in another way.

Hitchock (1995) defines the computational simulation expression as an algorithm that mimics a physical problem.

In the computational simulation presented in the work of Tavares (2007) by using software ECOTECT v.5 to measure maximum and minimum luminance, we can observe that the surface generated by this software has the rectangular grid model and representation in perspective. On the surfaces generated by software SAP 2000 used by Thomazini *et al.* (2004) we have the rectangular grid model class and representation in perspective. However, for the surface generated by the software ANSYS used by Giuliatti *et al.* (2002) we have the rectangular and triangular grid model classes with plane representation and its projection on the XY plane. In the paper presented by Guello *et al.* (2002) the surface generated by QUEBRA2D shows the triangular grid model class and plane representation and its projection on the XY plane.

According to Cavira (2003) the computational simulation has become more and more important as a tool for knowledge acquisition as the problems´ complexity grow, hence the need to use a more systemic and generalist approach.

Softwares, since they are not perfect tools and have their limitations, help visualize and predict the behavior of the surfaces in study, but they cannot generate precise and reliable answers if the professional does not know the tool and understands the results generated by him.

According to Tavares (2007) the surface computational simulation makes possible quantitative and qualitative studies, taking into consideration that those studies are possible only because besides the results generated by the numeric calculations, the tools enable the production and the representation of surfaces that can be visualizes in a realistic way.

Cormen *et al.* (2002) defines algorithms a computational procedure that turns a value or a set of values into entries – a sequence of computational steps that transform entry data (parameters established) and produces some value or set of values as exit – exit data (software response: numeric result, graphic representation of surfaces or curves)

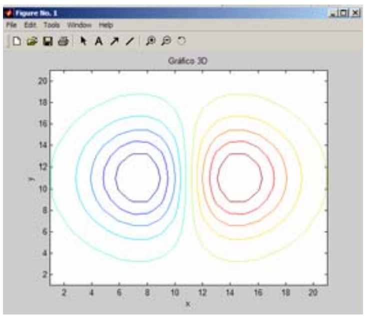
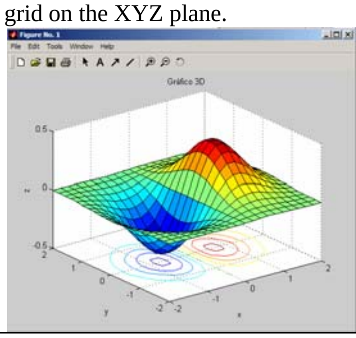
MatLab was developed in the beginning of the 80´s by Cleve Mole, at the Department of Science and Computing of the University of New Mexico, USA Tonon (2009).

MatLab has quite powerful tools for several kinds of applications, not only for engineering but also other areas. Therefore, MatLab only needs to be updated through specific commands Silva *et al.* (2004), Santos (2005).

According to Miranda *et al.* (2007) the great advantage MatLab has in comparison to other languages such as C and Fortran consist in the fact that in MatLab information is easily storable in matrixes, which provide an easy and fast manipulation of a great amount of information and the familiarization with the software's interface.

Definitions, concepts, applications and tutorials of use for generation of surfaces by using MatLab can be consulted with more details in Silva *et al.* (2004), Santos (2005), Tonon (2009), The Matworks (2000). Tab. 1 presents examples using software MatLab in order to represent the surface computational simulation.

Table 1. Examples using MatLab software to represent the surface computational simulation

Iso-value curves simulation on MatLab using *contour* command that shows the projection of the surface over the XY plane. 	Surface simulation plotted on MatLab with the *surfc* command. In the graphic representation of the surface we can identify that MatLab uses iso-value curves and perspectives. The construction of the surface model and rectangular grid on the XYZ plane. 

4. LOAD CELL CIRCULAR SURFACE SIMULATION

In order to carry out the load cell circular surface simulation, a research was performed on pressure transducers circular diaphragms. Pressure transducers are composed by a diaphragm that se deforms in the presence of a pressure gradient. This deformation is then measured by the tension sensors (strain gage) that are stuck to the diaphragm. The materials frequently used for the production of diaphragms pressure for sensors are the ferrous materials, metal alloys, latex, polymers among others. The use of pressure transducers nowadays involves a wide range of applications such as commercial, automation and industrial process control and in the health area. Thus, pressure transducers are mechanical structures, planned to receive efforts and deformer-se inside an elastic regime to which they were designed.

4.1. Material selection process for load cell circular diaphragms

The diaphragm model for load cell is similar to a circular plate with clamped boundary. According to Ashby (1992) the pressure sensor diaphragm deflection is provided by Eq. (1):

$$St = \frac{C_1 p R^4 \left(1 - \nu^2\right)}{E t^3} \tag{1}$$

Where:

St = diaphragm deflection;
p = pressure over the diaphragm;
t = diaphragm thickness;
ν = Poisson coefficient;
E = elasticity module;
R = load cell diaphragm radius.

Thus, for the engastada diaphragm borda or extremity we have: $C_1 = 3/16$, for the free extremity or borda we have: $C_1 \approx 9/8$. Fig. 5 presents the deflection to the pressure sensors diaphragm traction with clamped boundary.

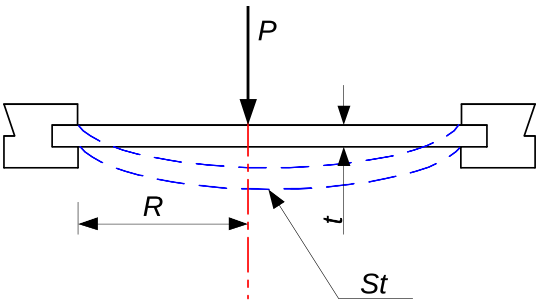


Figure 5. Deflection to diaphragm fraction Ashby (1992)

The maximum deformation of the load cell diaphragm traction is provided by Eq. (2).

$$\sigma_{max} = C_2 p \frac{R^2}{t^2} \quad (2)$$

For the clamped boundary or extremity we have: $C_2 \approx 1/2$, for the free extremity or borda we have: $C_2 \approx 3/2$.

The pressure sensor diaphragm radius is defined in the project and its thickness can vary according to the strain gage that will be used in the project and the maximum tension to the load cell diaphragm keeps restrained in Eq. (3):

$$\sigma_{max} = \sigma_f = C_2 p \frac{R^2}{t^2} \quad (3)$$

For a diaphragm with clamped boundary, the deflection to the maximum tension is provided by Eq. (4) and Eq. (5):

$$St = \frac{0{,}1875 pR^4 \left(1 - \nu^2\right)}{Et^3} \quad (4)$$

$$\sigma_f = 0{,}5 p \frac{R^2}{t^2} \quad (5)$$

Replacing the variable *t* in Eq. (5) in Eq. (4) we have the deflection for the load cell diaphragm Eq. (6) Ashby (1992):

$$St = \frac{0{,}5304 R \left(1 - \nu^2\right) \sigma_f^{\frac{3}{2}}}{Ep^{\frac{1}{2}}} \quad (6)$$

Possessing the Eq. (1 to 6) and the propositions provided by Ashby (1992), we employ the material selection procedures suggested by Forcellini (2003) and as an auxiliary tool the multi-criteria and performance index methods are used.

1st Step – Analyze the material selection requirements.

2nd Step – Determine the material critical priorities: Identify the attribute or criterion to be maximized or minimized; develop the criterion function or the objective function, in terms of functional requirements, or the material geometry and property; identify the project's free variables, that is, the ones that can vary freely; identify the restrictions and the order of importance; develop restriction equations; replace the free variables of the restriction equations in the criterion function; gather the variables into three groups; functional (F); geometry (G) and material properties (M); identify the performance index, expressed with the amount M, to be optimized.

3rd Step – Classification of the possible materials. On this step, it is already possible to get to the materials, Ashby (1992) suggests some materials and their advantages and disadvantages according to Tab. 2 and Fig. 6.

Table 2. Possible Materials for the diaphragms Ashby (1992)

Material	$M = \left(\sigma_f^{\frac{3}{2}}/E\right)(MPa)^{\frac{1}{2}}$	**Loss Coefficient (η)**	**Comments**
Ceramic	0,3 - 3	$< 10^{-4}$	Very good *M* value, but not able to stand traction efforts.
Glass	0,5	$\approx 10^{-4}$	Possible if protected from dangers.
Spring Steels	0,3	$\approx 10^{-4}$	Represent the standard choice, have low attrition coefficient, fast response and difficult to be machined.
Titanium Alloys	0,3	$\approx 3 \times 10^{-4}$	They are as good alloys as steel, represent resistance to corrosion, but very expensive.
Polymers: Nylon Polypropylene HDPE* Teflon	0,3 0,3 0,3 0,3	$\approx 2 \times 10^{-2}$ $\approx 5 \times 10^{-2}$ $\approx 10^{-1}$ $\approx 10^{-1}$	Present problems like flowing and high attrition coefficient, generating sensors with reproductivity reduced.
Elastomers	0,5 - 10	$\approx 10^{-1} - 1$	Excellent *M* value, high elastic deflection, great loss of the coefficient, which limits the response time.

*High density polyethylene.

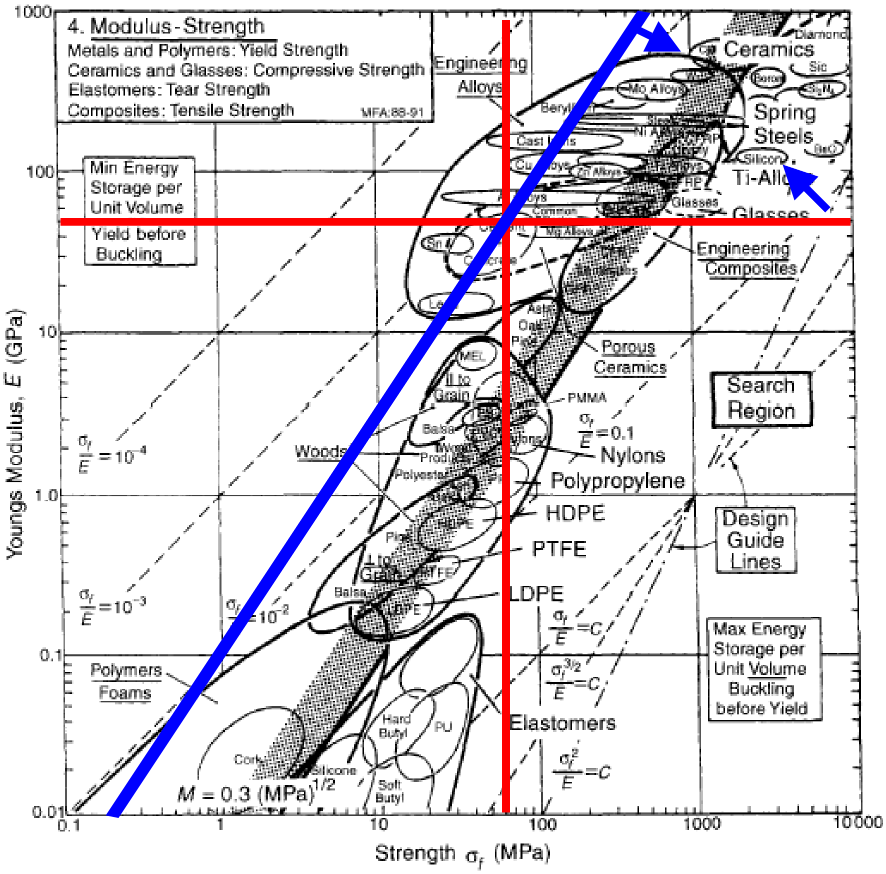


Figure 6. Materials for elastic diaphragm Ashby (1992)

4th Step – Selection of the possible material.
5th Step – Project data development.

4.2. Load cell diaphragm project proposal

The material chosen for the load cell production was aluminum, according to the performance index method and the multi-criteria. Below we list some of the aluminum's characteristics for the load cell production. Aluminum alloy:
- Elasticity Module = 70 GPa; Poisson Coefficient = 0,33; Maximum Deformation tension = 1000 MPa.

The load cell model to be presented and their dimensions were base don the data by Timoshenko (1975) and Doebelin (1990)

For Ashby (1992) determining the diaphragm's maximum thickness needs its maximum deformation tension. The thickness can be found from Equation 5:

$$t = \sqrt{\frac{0,5 \times p \times R^2}{\sigma_f}} = \sqrt{\frac{0,5 \times 89 \times 10^6 \times \left(10 \times 10^{-3}\right)}{1000 \times 10^6}} \cong 2 \times 10^{-3} m$$

Where:

p – pressure 70 Kgf [≈ 89 MPa]; t – diaphragm thickness in [mm];

R – radius [mm]; σ_f - maximum deformation tension [MPa].

With the material already selected and the dimensions suggested by Timoshenko (1975) and Doebelin (1990), what is interesting now is the diaphragm thickness. For Doebelin (1990) the diaphragm thickness is determined from the strain gage sensitivity, Poisson coefficient and the elasticity module of the material to be used on the production of the load cell. In the case of diaphragm of homogeneous thickness, when submitted to a constant pressure, it is subject to two kinds of tensions; a traction tangential tension, equal on the two faces of the diaphragm, and another one, radial tension, with contrary signal on the two faces Fig. 7.

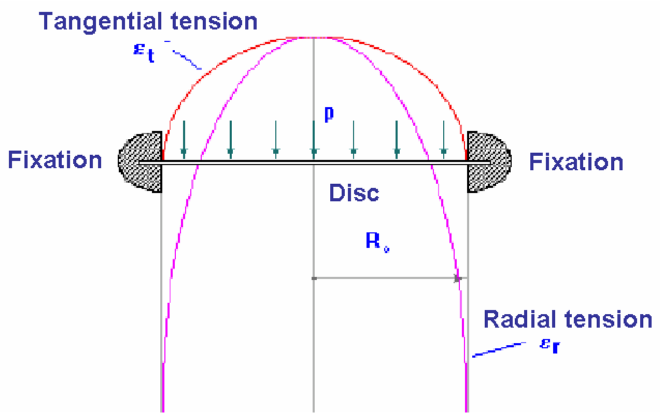


Figure 7. Distribution of tensions on the diaphragm Doebelin (1990)

For small deformations, the values of the tangential tensions and radials presented on Fig. 9 can be obtained by equations Eq. (7) and Eq. (8).

$$\varepsilon_t = \frac{3(1-\nu^2)(R^2 - r^2)}{8Et^2} p \tag{7}$$

$$\varepsilon_r = \frac{3(1-\nu^2)(R^2 - 3r^2)}{8Et^2} p \tag{8}$$

Where:
p – pressure on the diaphragm [MPa];
t – diaphragm thickness [mm];
r – current radius, where we can verify the tensions ξ_t e ξ_r [mm];
R – exterior radius (fixation) [mm];
v – diaphragm material Poisson coefficient [undimensional];
E – elasticity module [GPa].

The tension diaphragm shows that the tangential tension is always positive and the radial tension has a zone where it is positive and anther one where it is negative, therefore it is null for a determined value of diaphragm radius. The calculation of the diaphragm thickness by Timoshenko (1975) and Doebelin (1990) is provided by:

$$t = \sqrt{\frac{820 \times 89 \times 10^6 \times (10 \times 10^{-3})^2 \times (1-(0,33)^2)}{70 \times 10^9 \times 0,60 \times 10^3}} \cong 2 \times 10^{-3} m$$

Where:
p – pressure 70 Kgf [≈ 89 MPa]; *t* – diaphragm thickness in [mm];
R – radius [mm]; *v* - Poisson Poisson [undimentional];
E – elasticity module [GPa]; y_c – sensor sensitivity (strain gage) [mV/V].

Fig. 8 shows an extensometer of four elements used in the measure of the radial and tangential diaphragm deformation.

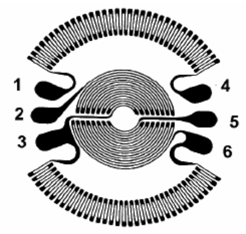


Figure 8. Extensometers used in diaphragms Doebelin (1990)

The extensometers of the exterior zone are supposed to measure the radial tension and the interiors of the tangential tension measure. The extensors are connected in Wheatstone bridge, with the exteriors of the R1 and R3 branches and the interiors of the R2 and R4 branches. With this assembling, of four active extensometers, the Wheatstone bridge sensitivity increases and the effect of the temperature on the extensometers is cancelled. The relation between the exit tension and the pressure is linear, with error below 0,3% as long as the diaphragm deformation in the central zone is below 1/4 of the thickness. The diaphragms are dimensioned in order to fulfill this criterion. It is possible to measure the maximum frequency with this equipment, depending on the dimension of the mechanical elements, and if there are sensors capable of working from 0 to 10 kHz. The proposal of the load cell prototype, its dimensions and the diaphragm thickness are provide by Fig. 9.

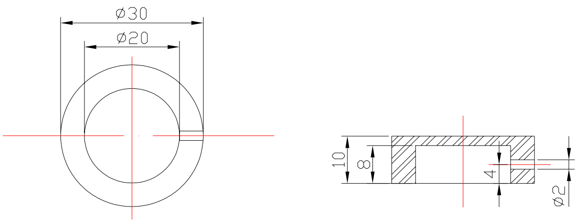


Figure 9. Load Cell Prototype

4.3. Load cell diaphragm circular surface simulation

For the load cell diaphragm circular surface simulation presented on Fig. 10 a 70 Kgf force and a 2,0mm thickness were used with the meshgrid function. With the force applied on the circular surface, it will suffer maximum deformation. The model of the surface generated is rectangular grid on XYZ plane. The simulation with meshgrid function was carried out in the points x = 50 e y = 50 in order to verify the model of the surface generated.

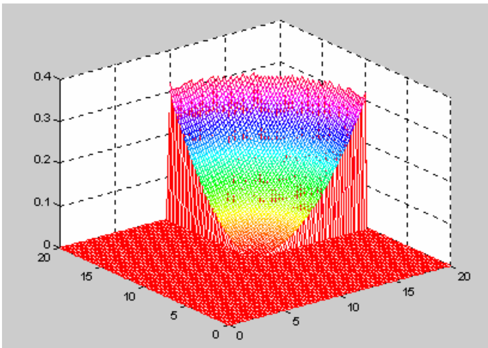


Figure 10. diaphragm maximum deformation on the points x = 50 and y = 50

On Fig. 11the same 70 Kgf force was applied on the circular surface and for the simulation a cut was performed on the points x = 20 e y = 30 with the meshgrid function in order to generate the model of the surface generated. The model of the surface generated was rectangular.

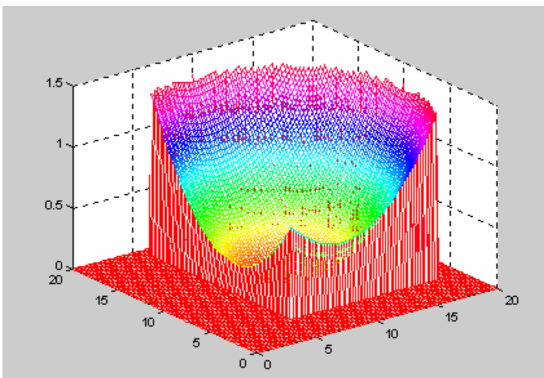


Figure 11. Diaphragm maximum deformation on the points x = 20 and y = 30

We can observe that MatLab software is an excellent tool to carry out surfaces simulation employing the rectangular grid model not only on the XY plane but also on the XYZ plane.

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