Semester project June 2017

Advanced NanoElectroMechanical Systems Laboratory

Finite element optimization of a silicon nitride membrane

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Contents

1 Introduction

Membranes are wisely used for Micro and nano electromechanical systems, in particular as a pressure sensor [4] and [9]. In order to determine the mechanical behavior measurement of the deflection of the membrane with respect to the applied pressure as shown figure 1 has to be preformed.

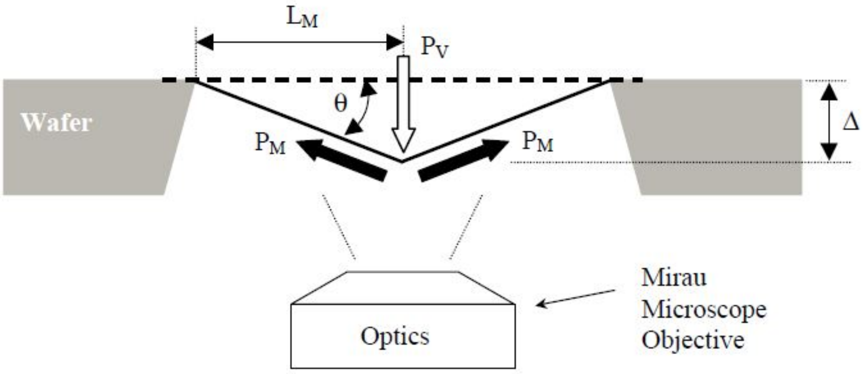

Figure 1: Schema of functionality of on sensor device by the measurement of the deflection of a membrane with respect to applied pressure [4]

As this technology develops itself the demand of the industry increase, one of the main factor of improvement is the deflection sensitivity with respect to applied pressure while keeping a linear behavior and a cutoff frequency as high as needed. In this project, the optimization by finite element of those three factors for the device schematically presented in the figure 2 is investigated.

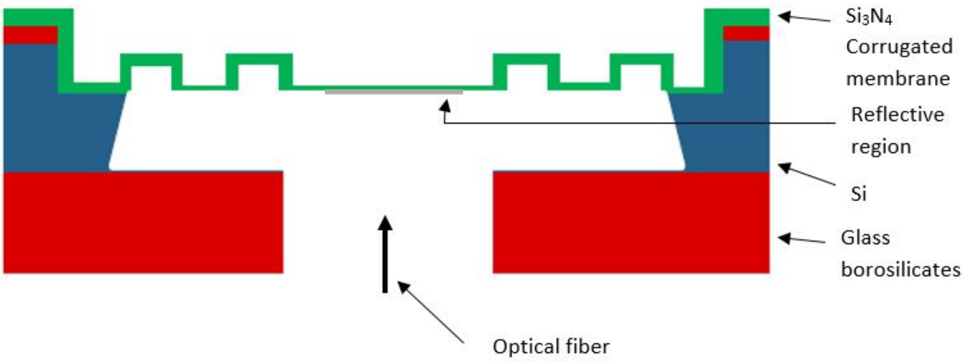

Figure 2: Schema of the device of study

In this device the measurement method is done by a optic fiber hence the need of a 30 nm thickness reflective region. The first step is to describe the numerical model. Then, the influence of the parameters for a simple flat SiN membrane is investigated before the implementation of the reflective region. And finally corrugations are going to be studied in order to give a final design.

2 State of art

Many authors have studied the influence of parameters on the deflection, the linearity and the cutoff frequency for membrane nano mechanical devices. The shape off the membrane itself has been studied by Khakpour in 2010 [5] proving that the largest center deflection can be obtained in circular diaphragm, but they also have the lowest cutoff frequency with respect to square once or rectangular ones. The geometry with the better tread off is the square one. In fact, as the deflection increase the first natural frequency as well as the linearity decrease. One solution in order to provided the necessary compliance or rigidity needed for the membrane is to modulated the press stress or the thickness as the lower it is the more compliant is the diaphragm, like it is possible to see in the figure 3. [1] and [3].

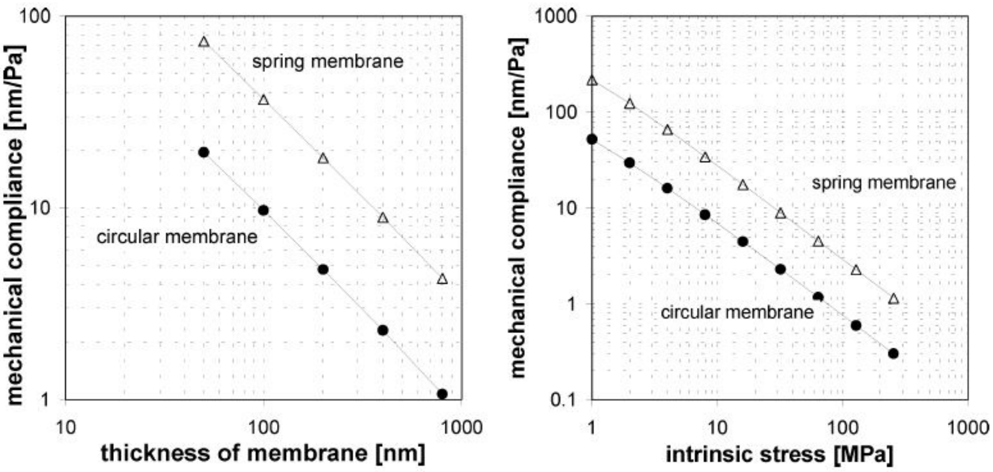

Figure 3: Simulated mechanical compliance of a circular and spring membrane diameter 1 mm versus thickness of the membrane intrinsic stress 30 MPa and versus intrinsic stress, respectively membrane thickness 400 nm [3]

But others solutions are studied. The first one is the membranes with holes, like presented in the figure 5 studied by Ming Chen [7]. This indeed, increased the compliance significantly to reached a high sensitive with low voltage by releasing the prestress in the membrane. But with this solution with a membrane of 600 μm of diameter and a thickness of 180 nm and initial prestress of about 300 MPa the cutoff frequency is of 33 kHz. An other idea is presented by Silder in [6] which consist of a pattern done by lithography like presented figure 4. More over in this study the membrane is supported by thick cantilevers that also allows more compliance, figure 4.

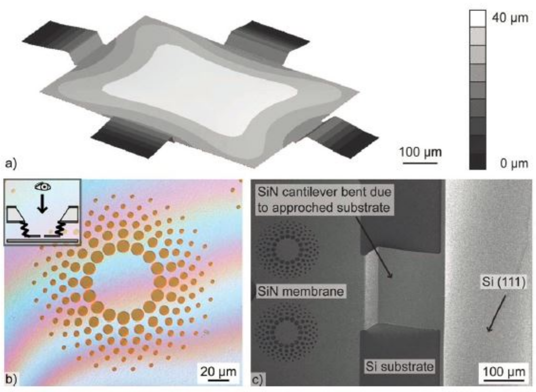

Figure 4: (a) Result from a finite element method (FEM) simulation showing that a square membrane supported by four 200 mm long and 500 nm thick cantilevers deflects 40 mm under a load of 45 mN. (b) Optical illustration taken of a compliant SiN membrane placed on a Si substrate. (c) SEM illustration of a deflected beam of a compliant stencil membrane in contact with a Si wafer. [6]

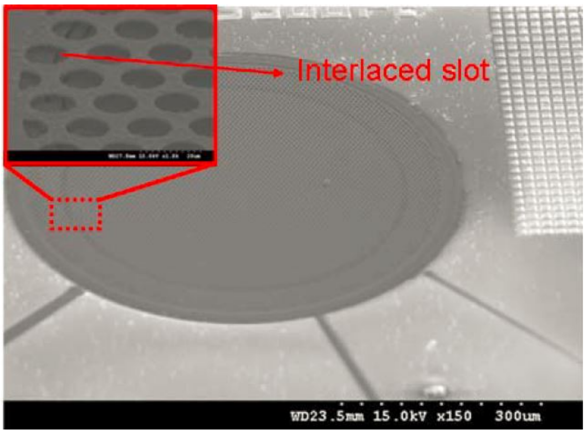

Figure 5: Photography of a membrane with holes[7]

The most widely studied solution is the implementation of corrugations. They can be used to rigidify and expand the linear behavior depending on the pattern [2], [8]. The figures 6 and 7 presented more compliant membrane patterns. In fact, Fulnder [3] has studied circular pattern and proves that corrugated membrane behaves like planar membranes with reduced stress and that it depends on the ratio of the corrugation height to the thickness of the membrane and that the sensitivity is increased by a factor 8 with 8 corrugations, the intrinsic stress deceased by a factor 5, and so also the cutoff frequency. In [1] they managed to reached a sensitivity of 40nm/Pa with a cutoff frequency at 60 kHz with a linearity range until 50 Pa with four corrugation on a 1mm length, 620 nm thickness and the corrugation size of 10x3.3 μm corrugation. This represents a increase of factor 6 of the sensitivity and a decreases of 3 the cut off frequency.

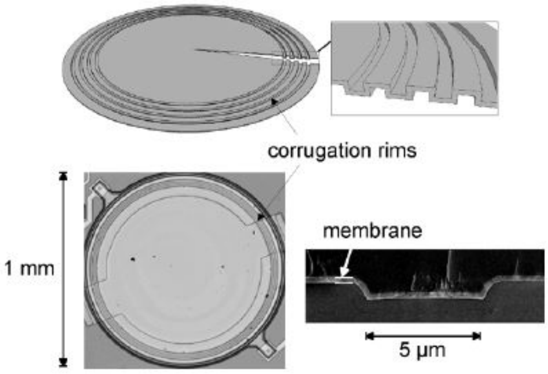

Figure 6: Three dimensional representation micro graph and cross section of a corrugated membrane [3]

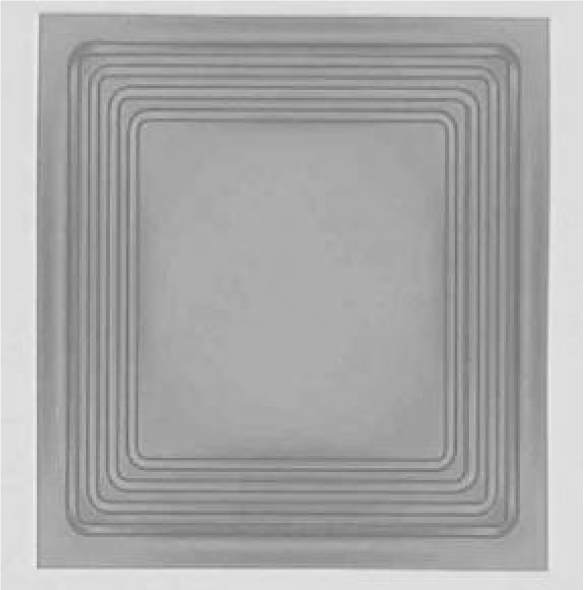

Figure 7: Photography of a membrane with four corrugations [1]

As in this project specifications presented in the next section have to be reach a finite element optimization of all the parameters involved is performed.

3 Goals and followed steps

The goal of this study is to optimize a pressure sensor membrane. The following specifications should be reached :

- The first eigenfrequency : 100 kHz
- Limit of detection of 0.5 nm at 0.02 Pa
- Dynamic range of linearity from 0.02 Pa to 20 Pa

A finite element analysis is used to fulfill the optimization, Ansys APDL software is chosen in order to be able to computed more easily an adaptive geometry. The figure 8 present the different steps followed during this project to fulfill the objectives. Each step is then detailed in the following sections.

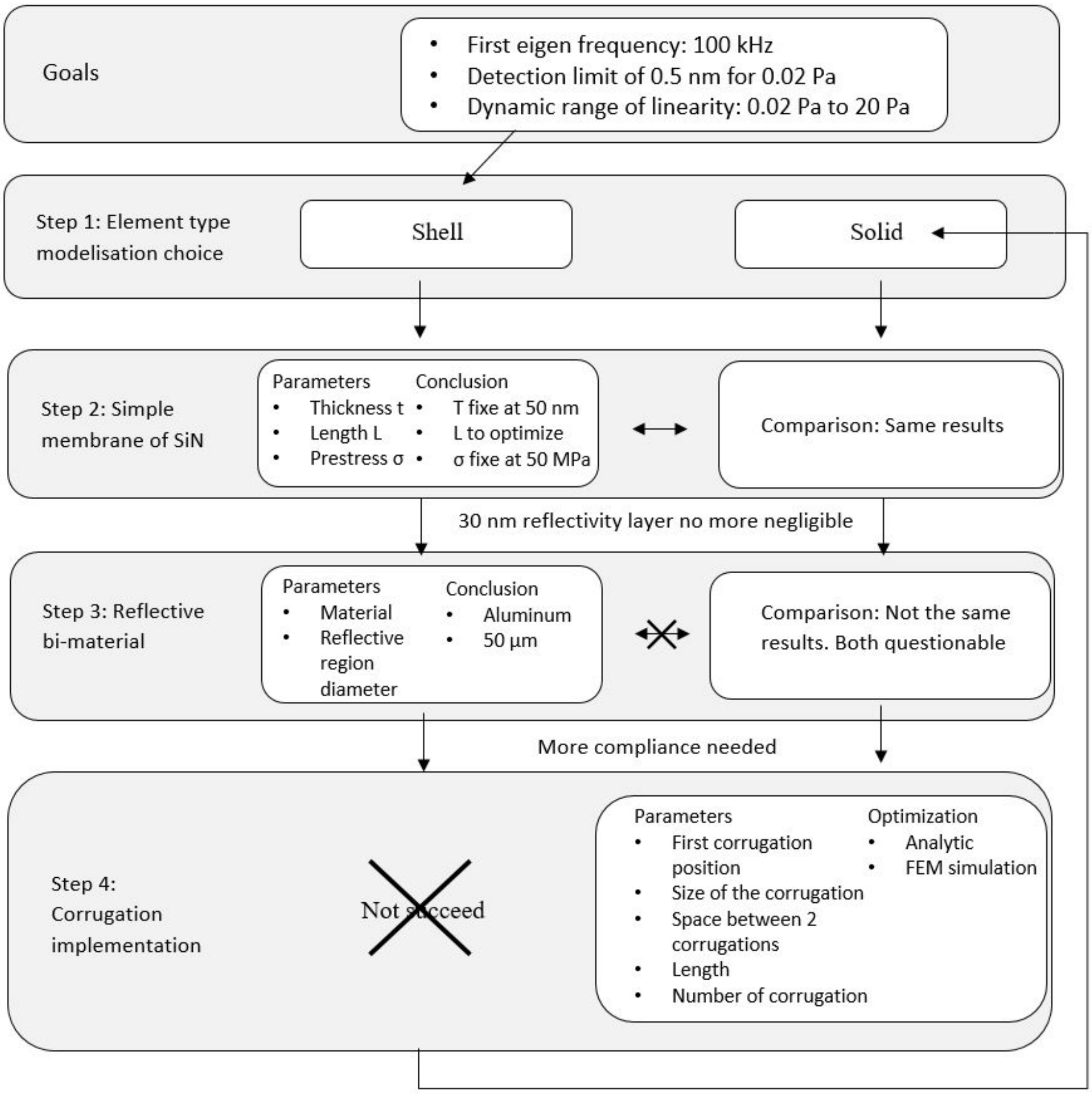

Figure 8: Followed steps explicative schema

4 Numerical model description for all steps

As justified in the state of art a square membrane shape is used in order to keep the better compromised between compliance and cutoff frequency. Two type of analysis are going to be computed. The first is a modal analysis in order to determine the first natural frequency. It is to be noted that the membrane are submitted to a prestress, so the PSTRESS,ON command has to be activated. Moreover, the prestress is applied only on the x and y direction with the command :

$$
\begin{aligned}
&INISTATE, SET, MAT, 1\\
&INISTATE, DEFINE, , , , , stress, stress\\
&ALLSEL, ALL, ALL
\end{aligned}
$$

Here, the prestress of value "stress" is applied in the direction x and y of all the element with the material 1 previously defined. The second analysis is a static analysis to determine the displacement from 0 Pa until 20 Pa. The first 2 Pa are discretized by a step of 0.01 Pa then from 2 Pa to 20 Pa the step of 1 Pa is taken. As large displacement can occur it is important for all the simulation to activate the non linearity geometric by the NLGEOM, ON command in the sol solver. The pressure is applied on the node of the mesh. The unit system used is the μMKs $[\mu m, MPa, kg, s, C°]$. As the boundaries conditions, the load case and the first eigenmode are symmetric, a double symmetry in x and y is used to compute the membrane. The symmetry conditions are the blocking of the normal displacement to the surface and the rotation of the two other direction. Figure 9. An anchor part is modelise and clamped at the extremity of the membrane in order to compute the boundary conditions. This condition is presented figure 9. Indeed, the membrane is glued to a glass structure like also presented figure 2.

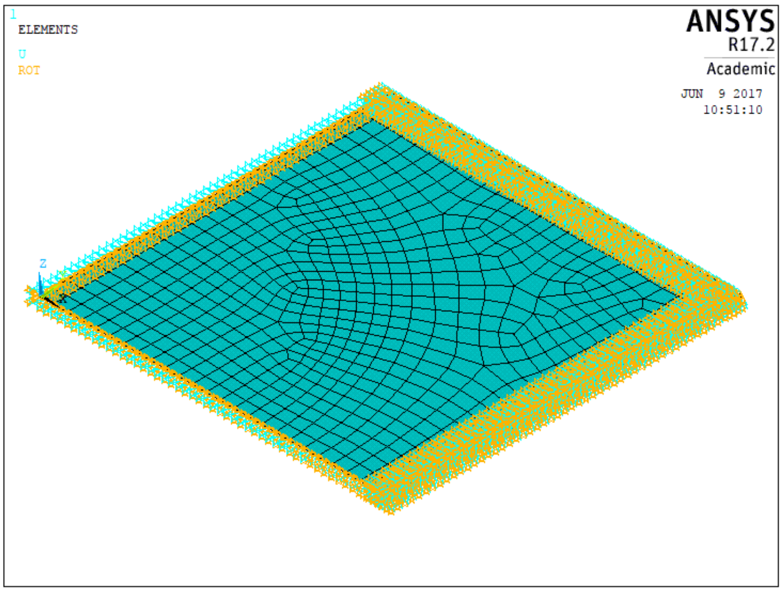

Figure 9: Symmetry and boundaries conditions modelisation

All the materials used are considered linear, isotropic and elastic. And the mechanical properties of each material needed for the simulations are resumed in the table 1.

Table 1: Material properties

	Silicon nitrite	Gold	Aluminum
Young's Modulus [MPa]	200e3	78e3	75e3
Poisson coefficient [-]	0.25	0.42	0.33
Density [kg/μm]	3300e-18	19300e-18	2700e-18

The SiN is used for the membrane. The analysis of the choice between gold or aluminum for the reflectivity region described in the figure 2, is going to be developed section 7. The pres stress of the silicon nitrite can varies from 50 MPa to 900 MPa. For the gold and the aluminum the usual pre stress is compressive one of about -100 MPa.

5 Step 1 : Element type for the modelisation choice

The first choice of modelisation was the shell element. In fact, as the model is a membrane with a t/L ratio of maximum 0.05% this element type seemed more appropriated. The shell element node has 5 degrees of freedom (the three displacement and the x and y rotation) as the solid one have only 3 degrees of freedom, only the three displacements. The shell element are hence more able to modelise the bending of a thin plate as for the solid element a numerical shear blocking can occur because lower-order bricks cannot 'bend' since they have linear sides. Hence, parasitic shear strains develop, and the traditional formulation is too stiff in bending. Moreover, the computational time is significantly reduced with shell elements. Unfortunately as the model with corrugations has not be able to be computed with shell element type, a model with solid element have also be developed. But to avoid the mechanical blocking an idea is to add internal 'bending' type of DOF to make the element more flexible in bending to alleviate shear locking. These are internal DOF. They are condensed out during element matrix formulation, so the user never sees these extra DOF. This can be applied by the command :

$$ET, 1, SOLID185$$
$$KEYOPT, 1, 2, 2$$

6 Step 2 : Simple membrane of SiN

The parameters than can be modulated in order to optimize the specification described above are the length, the thickness and the prestress applied. The range of study for the length is from 750 μm to 3500 μm, the one for the thickness is from 50 nm to 500 nm and the prestress applied can be modulated from 50 MPa to 900 MPa. A convergence analysis of the mesh on the displacement and on the first eigen frequency is performed. The parameters choice for this convergence is set arbitrary with a length of 950 um, a thickness of 50 nm and a prestress of 50 MPa. As the results should be linear the convergence for the other values of the parameters should be valid. This concerns both element types.

6.1 Shell element modelisation

The shell element used are the SHELL281 a quadratic 8-nodes element. The Ansys APDL code for the static analysis is found appendix 11.1.2. and the modal one appendix 11.1.1. The table 2 resume the number of nodes and the characteristic size of each mesh used for the convergence.

Table 2: Mesh characteristic size and number of nodes

Mesh number	Characteristic size [μm]	Number of nodes
1	5	201417
2	10	25588
3	20	7079
4	30	1541

The figure 10 and 11 present the relative error respectively between the displacement at the center find with the finer mesh and the others.

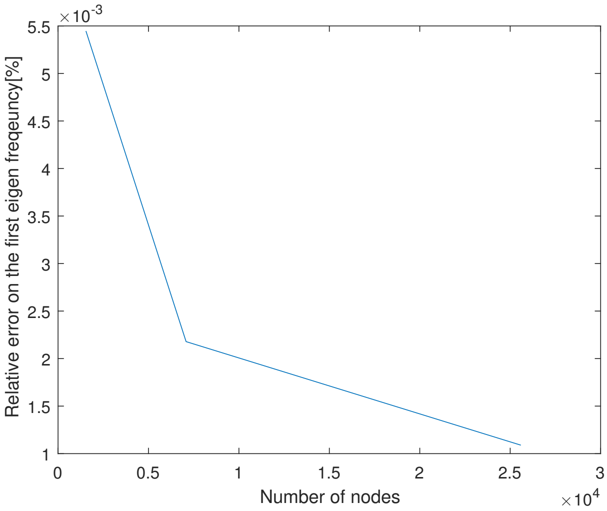

Figure 10: Convergence of the first natural frequency in function of the number of nodes

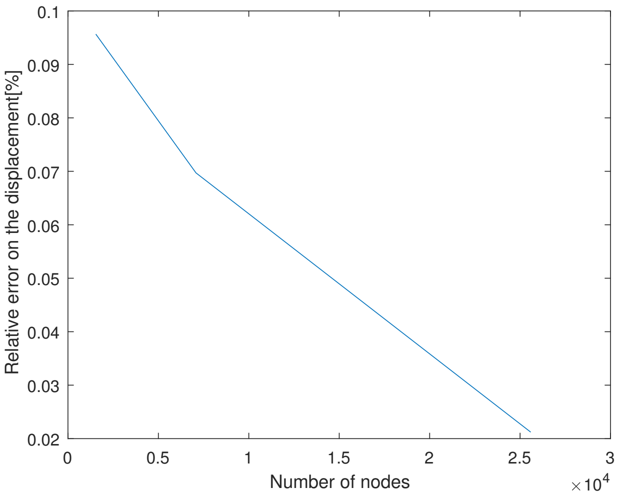

Figure 11: Convergence of the maximal displacement in function of the number of nodes

It is possible to see that the relative error is always under 1% for both the frequency and the displacement. This mean that for all the mesh sizes the results for the shell model are reliable. For the parameters chosen here the converged displacement for 20 Pa is of 0.527 um and the first eigen frequency is of 92 kHz.

The figures 12 and 13 present respectively a typical color plot for a the displacement and the first eigen mode for this geometry.

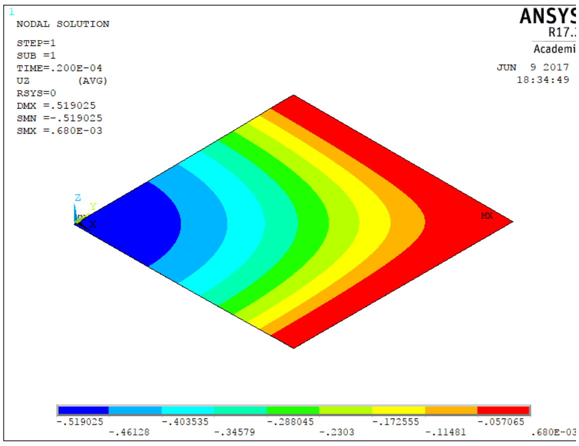

Figure 12: Color plot of the typical displacement of the membrane

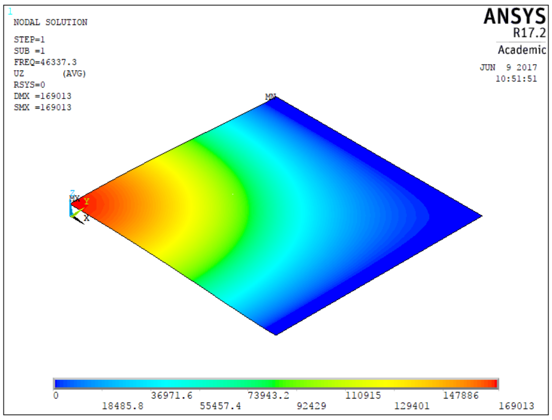

Figure 13: Color plot of the typical first natural frequency of the membrane

6.2 Solid element modelisation

The solid element used are the Solid185 a linear 8-nodes solid element. The linear form is chosen because the quadratic element do not support large displacement correctly. The Ansys APDL code for the static analysis is found appendix 11.1.4. and the modal one appendix 11.1.3.

Table 3: Mesh characteristic size and number of nodes

Mesh number	Characteristic size [μm]	Number of nodes
1	2	127008
2	3	57122
3	4	32258
4	11	4608
5	20	1458

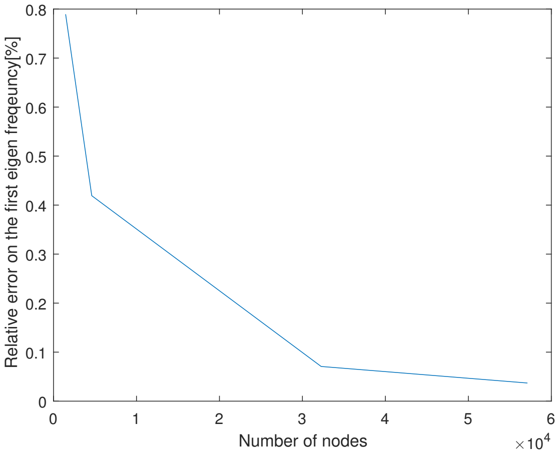

Figure 14: Convergence of the first natural frequency in function of the number of nodes

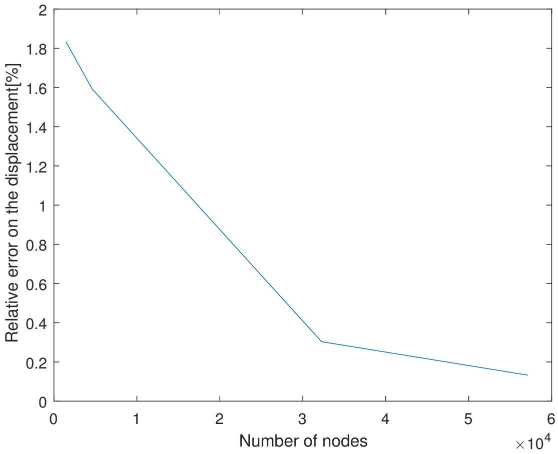

Figure 15: Convergence of the maximal displacement in function of the number of nodes

The exact same procedure is employed for the solid element. Here the convergence for the displacement is immediate but not for the frequency. In fact, it is possible to see that the relative error decrease under 1% only after refining until a characteristic size of 11 (4608 nodes). But the convergence is reached anyway. The results for the same parameters than for the shell element is of 0.519 nm of maximal displacement at 20 Pa and 91.8 kHz for the first eigen frequency.

6.3 Comparison and discussion

If the results of the sections above are compared a difference less then 1% is found. Meaning that either codes gives the same results, but the solid model need a longer computational time as the number of nodes needed is higher. Only the results for the solid model are now discussed. For all the values of the parameters the displacement is linear from 0 to 20 Pa. So only the results and the influence of the parameters on the first eigen frequency and the displacement for 0.02 Pa are going to be analyzed in the following. To highlight the influence of each parameters an initial geometry of a length 1 mm, a thickness of 50 nm and a prestress of 50 MPa is taken and once one parameters is modulated the two others are fixed. Thus the figure 16 presents the influence of the thickness on the displacement and on the first frequency each normalized by the objectives (0.5 nm and 100 kHz). The figures 17 and 18 present respectively the influence of the length and of the prestress.

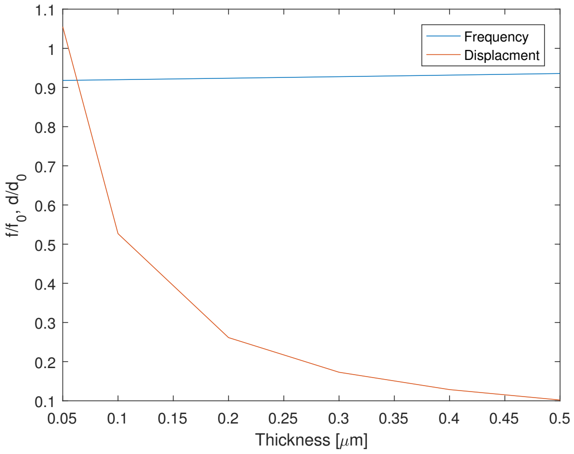

Figure 16: The influence of the thickness on the maximal displacement and on the first natural frequency for a simple SiN membrane

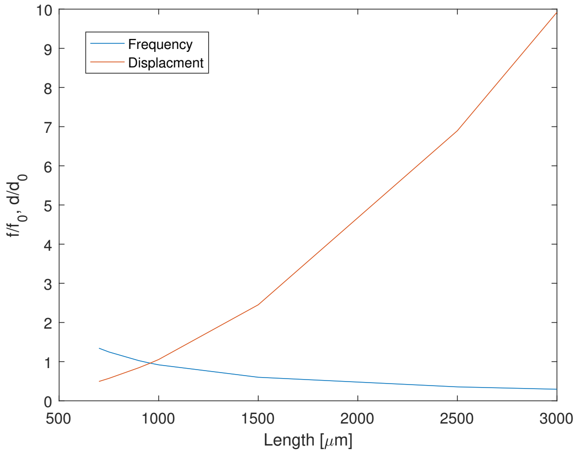

Figure 17: The influence of the length on the maximal displacement and on the first natural frequency for a simple SiN membrane

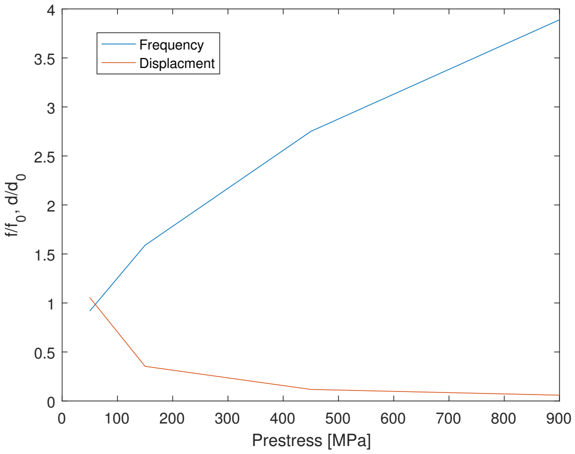

Figure 18: The influence of the prestress on the maximal displacement and on the first natural frequency for a simple SiN membrane

It is possible to observe that the thickness have a relative small influence on the first eigen frequency while thinner is the membrane higher is the displacement at 0.02 Pa. As the smaller admissible value of the thickness is 50 nm, in order to have a acceptable membrane life time, this value is going to be fixed.

For the length, longer is the membrane higher is the displacement but smaller is frequency, the same effect is observable with the decrease of the prestress, an optimize value must be found. Before the optimization, as the reflection region has a thickness of 30 nm it can not be negligible anymore. The next step of this report implement this bi material membrane.

7 Step 3 : Reflective bi-material membrane

For this step, the parameters are the material use for the reflective region and it's diameter. As said, the pre stress of the gold and of the aluminum is compressive. The membrane undergo an initial displacement that occurs due to the difference of pre stress. The same finite element are used as in the previous section. For the convergence studies an arbitrary membrane is taken of length 1 mm and a SiN prestress of 150 MPa.

7.1 Shell element modelisation

Once again the codes are present in appendix 11.2.1 and 11.2.2. To implement the reflective region at the center with shell element a circular region at the center is partitioned and a composite section of two material is computed. To assign the composite section to the right region a ASEL and a secnum command are used.

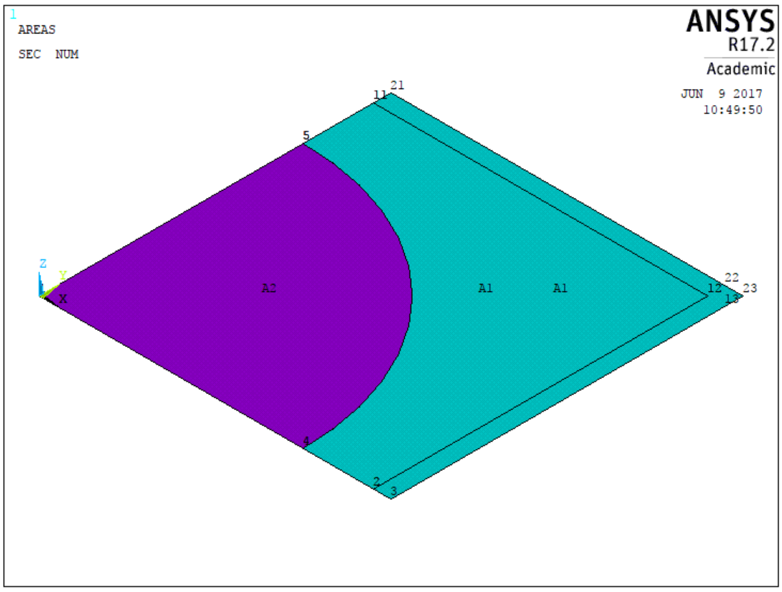

Figure 19: Bi material section for the shell element modelisation

The same reflexion for the convergence then the above section is effectuated and presented figures 20 and 21.

Table 4: Mesh characteristic size and number of nodes

Mesh number	Characteristic size [μm]	Number of nodes
1	3	71538
2	5	28960
3	8	11912
4	10	7853
5	20	5874

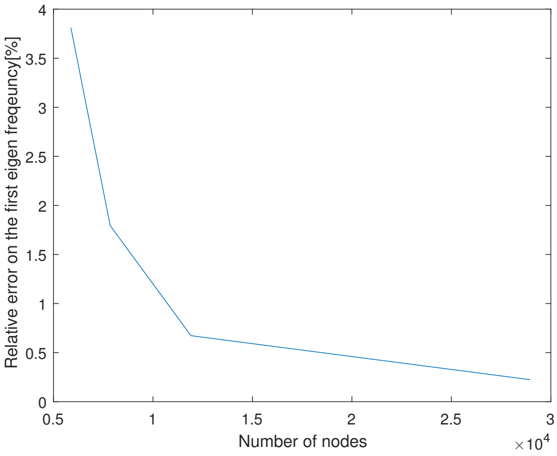

Figure 20: Convergence of the first natural frequency in function of the number of nodes

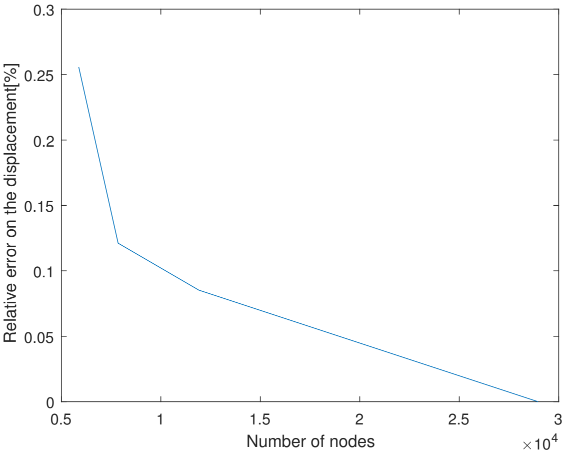

Figure 21: Convergence of the maximal displacement in function of the number of nodes

It is possible to see that the convergence is less easy to achieve for the frequency, the converge mesh for both subject of interest is then of a characteristic size of 8 μm.

7.2 Solid element modelisation

The codes are present in appendix from 11.2.3 to 11.2.6. For the solid model the two layers are modelised by two independent solid. More over it is necessary to partitioned like shown in figure 22 to be able to mesh with hexagonal element.

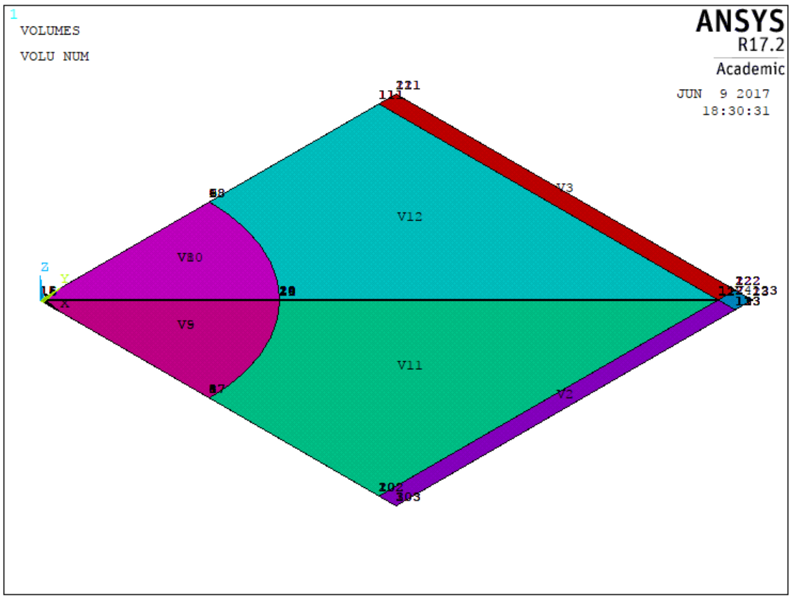

Figure 22: Partitioning of the solid model in order to be able to mesh in hexagonal element

Table 5: Mesh characteristic size and number of nodes

Mesh number	Characteristic size [μm]	Number of nodes
1	3	185679
2	5	67201
3	8	26767
4	10	17085
5	20	4417

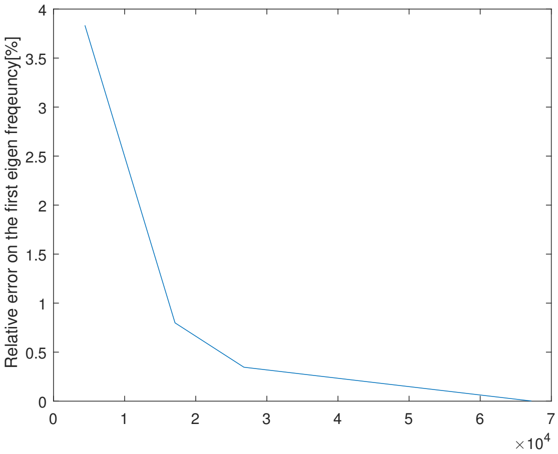

Figure 23: Convergence of the first natural frequency in function of the number of nodes

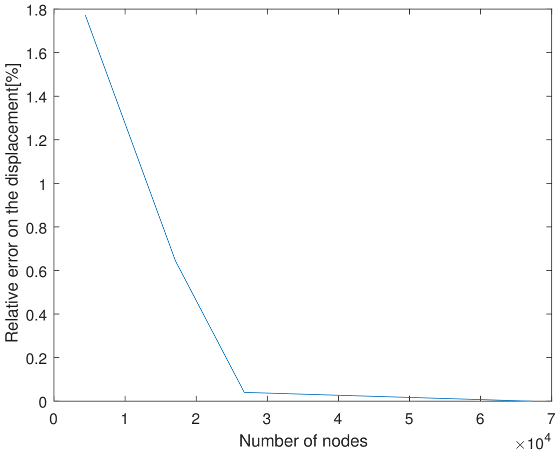

Figure 24: Convergence of the maximal displacement in function of the number of nodes

The convergence is also reached for a size of 4 um.

7.3 Comparison and discussion

If the difference is quantified a value of 30 % is found indeed the two simulation can not be compared anymore. The incertitude can come from both the modelisation as the composites section of shell do not handle correctly the difference of prestress, the corrugations model has not be able to be computed with shell element for the same reason. But, the interface of the two solid can also be source of errors. As the following of the study will be based on solid elements, those are going to be the studied simulations. Moreover, the influence of the material and of the size of the reflective region can be studied quantitatively as the results have reached their convergence.

First, a simulation with the same parameters once with aluminum and once with gold are compared. The first eigen frequency decrease of about 100% while the limit of detection increase only by 5 % when gold is used. This is predictable by comparing the Young's modulus that are similar while the density of the gold is 7 times higher. So, aluminum is chosen for the design.

Moreover the influence of the radius of the reflective region is also investigated. For those simulations the parameters are fixed to 450 MPa of prestress, the length at 1 mm and the thickness at 50 nm. The figure 25 present the displacement and the frequency in function of the reflective region radius.

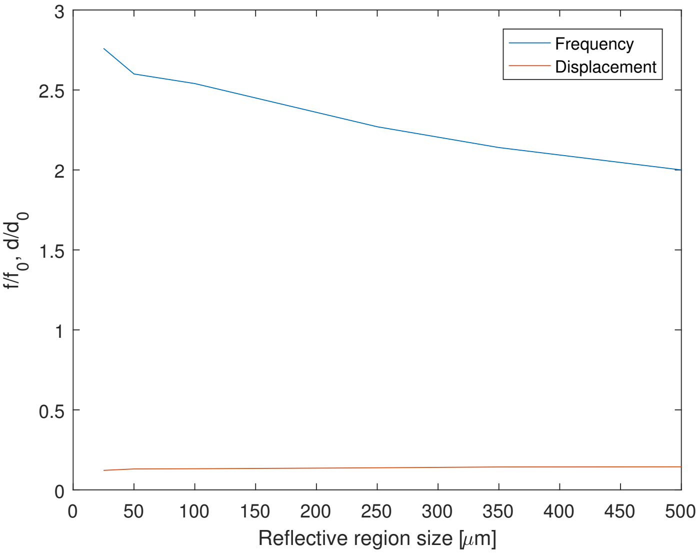

Figure 25: The influence of the reflective region radius on the first natural frequency and the displacement

It is possible to highlight that bigger is the region higher is the limit of detection but smaller is the frequency. Moreover, with those parameters the frequency of 100 kHz is easily reach but the limit of detection is to small. Meaning that the system has to be less rigid. So, the implementation of concentric circular corrugations is going to be studied and the influence on the factor f*d is going to be analyzed. If the term f*d is better for the same parameters then this solution is going to be preferred but otherwise corrugations that rigidify the structure should be implemented. In order to have to optimize the less parameters possible the region size is fixed at $25\mu m$ of radius, in fact as the increase of the radius does not have significant effect on the deflection while decreasing the frequency, the smaller the region is the better. Figure 25

8 Step 4 : Corrugations implementation

The corrugation have a rectangular section and their pattern is circular concentric as it is possible to see on the figure 26. In fact, as the goal is to be more compliant, so when the pressure is applied they have the possibility to relax.

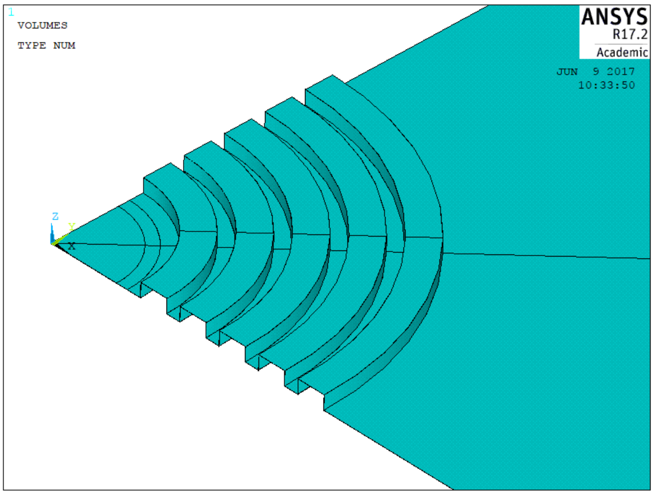

Figure 26: Corrugations representation

In order to modelise them and to be able to mesh them correctly 6 cylinders have been computed with the following commands like presented in the figure 27. The surfaces presented in the figure 27 are rotated over 90°. c_2 represent the distance between two corrugations, t the thickness, h the height of the corrugations, and c the width of the corrugations.

```
*DO,iii,1,iter,1
CYLIND,rc+((c+c2)*(iii-1)),rc+((c+c2)*(iii-1))+c2,0,t,0,90
CYLIND,rc+c2+((c+c2)*(iii-1)),rc+c2+c+((c+c2)*(iii-1)),h,t+h,0,90
CYLIND,rc+c2+((c+c2)*(iii-1)),rc+t+c2+((c+c2)*(iii-1)),0,t,0,90
CYLIND,rc+c2+((c+c2)*(iii-1)),rc+t+c2+((c+c2)*(iii-1)),t,h,0,90
CYLIND,rc+c2-t+c+((c+c2)*(iii-1)),rc+c2+c+((c+c2)*(iii-1)),t,h,0,90
CYLIND,rc+c2-t+c+((c+c2)*(iii-1)),rc+c2+c+((c+c2)*(iii-1)),0,t,0,90
*ENDDO
```

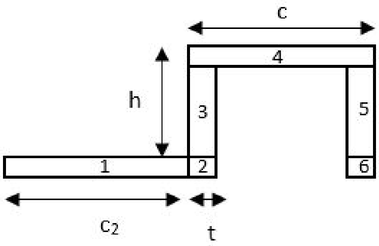

Figure 27: Schematic corrugations construction

The APDL code allows to modulated all the parameters involved :

- Length: L
- Thickness: t
- Prestress of the SiN: stress
- Prestress of the reflective region material: stress2
- Thickness of the reflective region: tg
- Radius of the reflective region:r (Must be strictly smaller than the position of the first corrugation)
- Material used for the reflective region
- Applied pressure: press
- Number of pressure step: nb
- Number of corrugation: iter
- Width of the corrugation : c
- Height of the corrugation : h
- Space between two corrugations : c2
- Position of the first corrugation : rc (Must be strictly higher than the radius of the reflective region)

The modal and the static analysis codes are given in appendix 11.3.

8.1 Convergence study

The first step is once again to preform a convergence study. The table 6 and the figures 28 and 29 present the characteristics and the relative error for the maximal displacement and the first eigen frequency between the result of the finner mesh and the others. This convergence study have been done on a single geometry with 2 corrugations.

Table 6: Mesh characteristic size and number of nodes

Mesh number	Characteristic size [μm]	Number of nodes
1	5	84064
2	7	44052
3	10	28174
4	20	19182

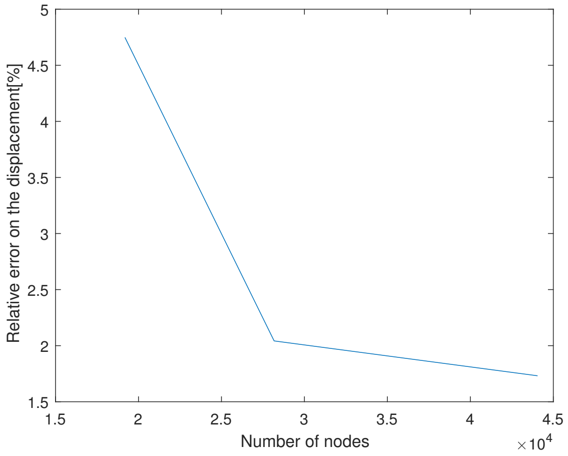

Figure 28: Convergence of the maximal displacement in function of the number of nodes

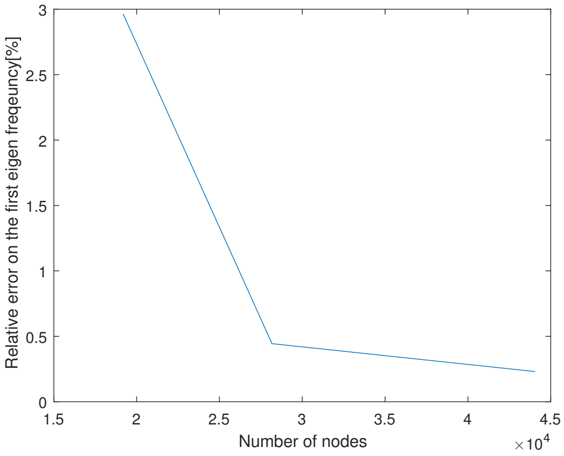

Figure 29: Convergence of the first natural frequency in function of the number of nodes

For the rest of this report all the simulation are produced with a 10 μm size.

8.2 Influence of each parameters

In order to highlight the influence of each parameters independently, one primary geometry is chosen with the following parameters and then each parameters is modulated independently:

- Length : 1 mm
- Thickness : 50 nm
- Number of corrugation : 1
- Height of the corrugation : 1.5 μm
- Width of the corrugation : 3 μm
- Pre stress of the SiN : 450 MPa
- Position of the first corrugation : 50 μm

With these parameters the first eigen frequency and the limit of deflection is :

- $f_0 = 268.4kHz$

- $d_0 = 0.0689nm$

Then all the parameters are fixed and only one is modulated and the following graphs can be computed. Except the thickness that is already fixed. The influence of the length and of the prestress of the SiN is not shown as the tendency is the same that the one presented figures 17 and 18. Once again for all the simulations performed the linearity until 20 Pa is reached so only the compromise between the first natural frequency and the limit of detection is studied. The results are normalized by 100 kHz for the frequency and by 0.5 nm for the deflection in order that the target for both is 1.

The figure 30 present the influence of the number of corrugation, it is possible to see that in fact as the deflection increase the frequency decrease. But the more interesting fact is that the figure 31 present the factor f*d that increase as the number of corrugation increase meaning that the presence of the corrugation with this pattern is beneficial to reach the specification.

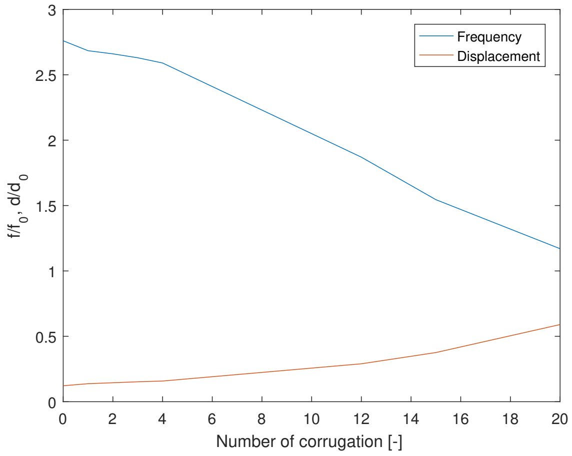

Figure 30: The influence of the number of corrugation on the natural frequency and on the limit of detection

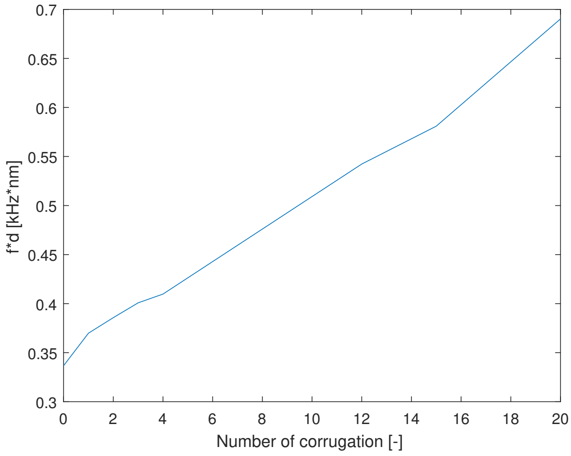

Figure 31: The influence of the number of corrugation on the factor f*d

The figure 32 present the influence of the position of the first corrugation. Farthest the corrugation is from the center better is the deflection but smaller is the frequency. If the factor f*d is analyzed in the figure 33 it is possible to see that the factor decrease with the position. This means that the optimize value is going to be near the center.

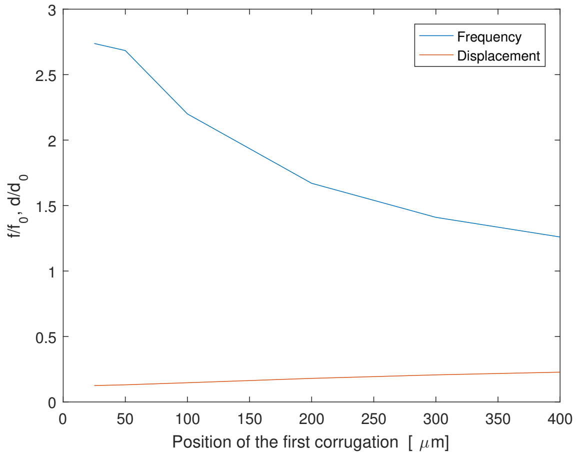

Figure 32: The influence of the position of the first corrugation on the natural frequency and on the limit of detection

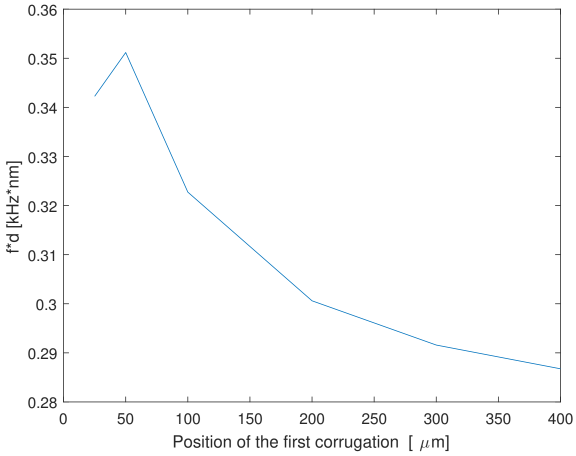

Figure 33: The influence of the position of the first of corrugation on the factor f*d

The figures 34 and 35 present respectively the influence of the height and of the width on the frequency and on the deflection. It is possible to see that the influence is negligible so these parameters are going to be fixed at a width of 10 μm and a height of 5 μm that gives good results while being convenient enough for the fabrication.

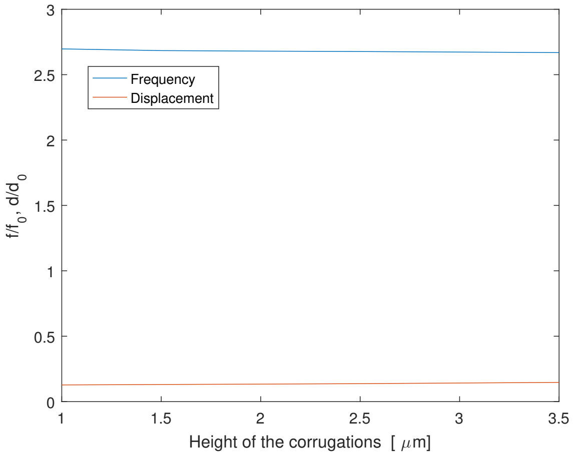

Figure 34: The influence of the height of the corrugation on the natural frequency and on the limit of detection

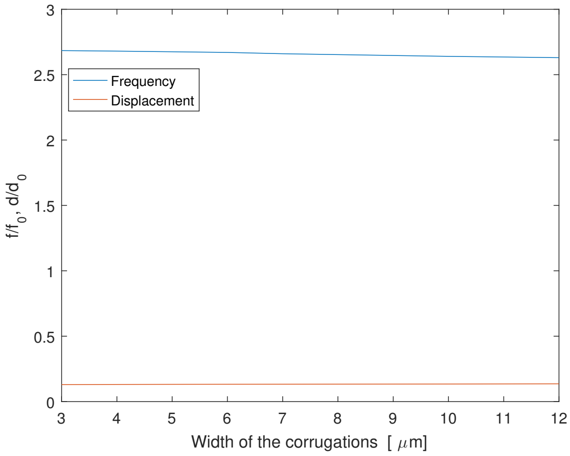

Figure 35: The influence of the width of the corrugation on the natural frequency and on the limit of detection

Moreover, as said the prestress has the same tendency so it is going to be fixed at 50 MPa. This is the smaller value position while maintaining good values of linearity. The study is performed again with the fixed new parameters.

The new primary parameters are then the following :

- Length : 0.7 mm
- Thickness : 50 nm
- Number of corrugation : 2
- Height of the corrugation : 5 μm
- Width of the corrugation : 10 μm
- Pre stress of the SiN : 50 MPa
- Position of the first corrugation : 25 μm
- Space between two corrugations : 5 μm

With these parameters the first eigen frequency and the limit of deflection is :

- $f2_0 = 124kHz$
- $d2_0 = 0.31nm$

The first parameters of investigation is the space between two corrugation as it is possible to see in the figure 36 this parameters also does not influence a lot the results so it also is going to be fixed at 5 μm.

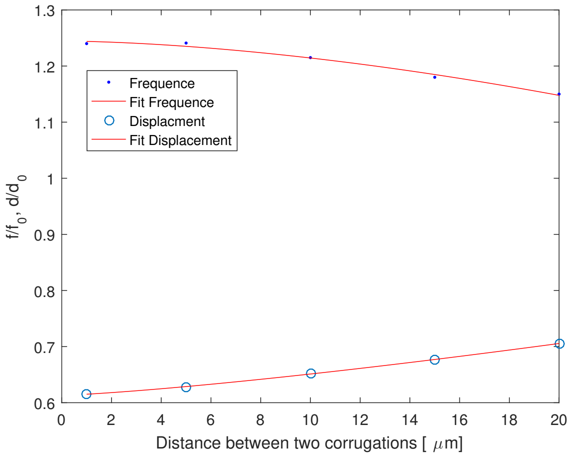

Figure 36: The influence of the space between two corrugations on the natural frequency and on the limit of detection

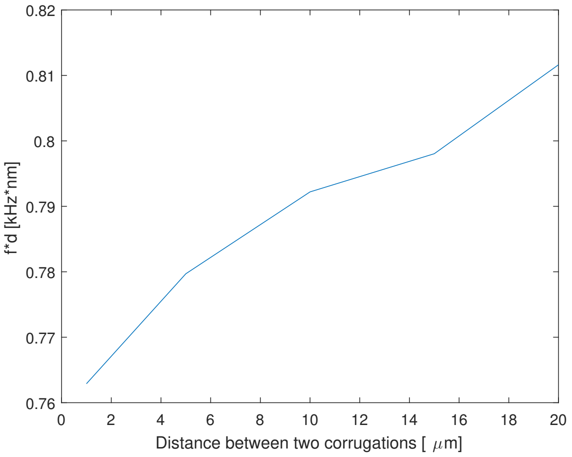

Figure 37: The influence of the space between two corrugations on factor f*d

The remaining parameters to optimize are :

- Length
- Number of corrugation
- Position of the first corrugation

To provide an analytic function to optimize those three parameters once again the parameters presented are fixed while only one is modulated. Then the results find are normalized by $f2_0$ and $d2_0$. Then by fitting the appropriate function on the curves of the figures 38, 40 and 42 an dimensionless factor representing the influence of each parameters can be found, and then by multiplying this by $f2_0$ and $d2_0$ the first eigen frequency and the limit of detection can be found for each value of parameters.

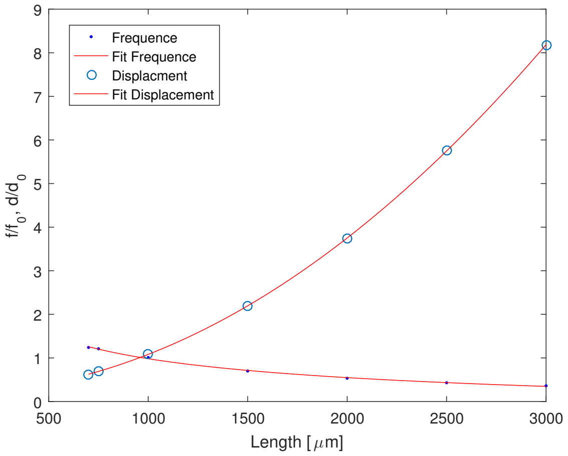

Figure 38: The influence of the length on the natural frequency and on the limit of detection

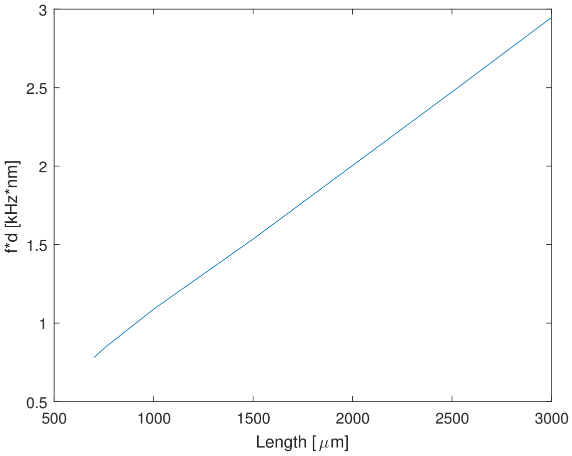

Figure 39: The influence of the width of the corrugation on the natural frequency and on the limit of detection

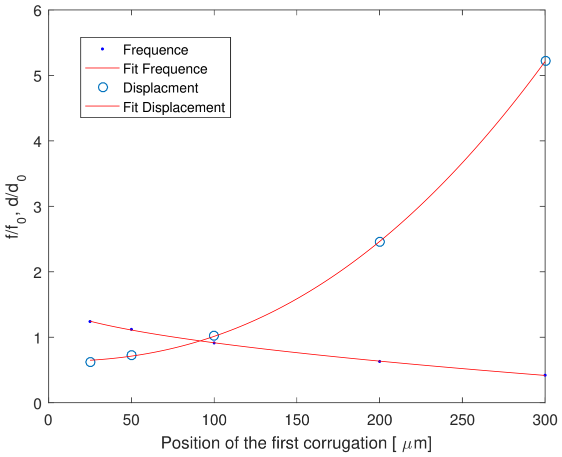

Figure 40: The influence of the position of the first corrugation on the natural frequency and on the limit of detection

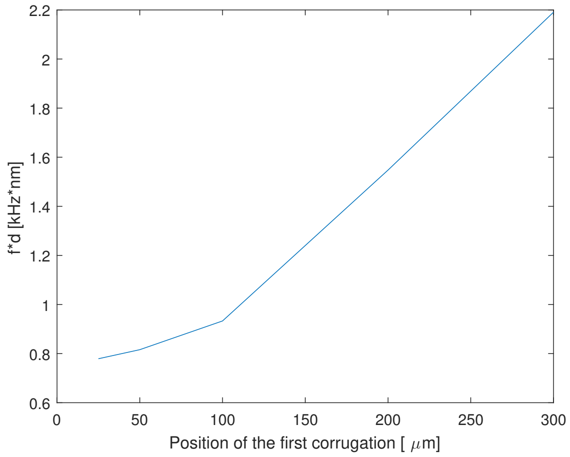

Figure 41: The influence of the position of the first corrugation on the factor f*d

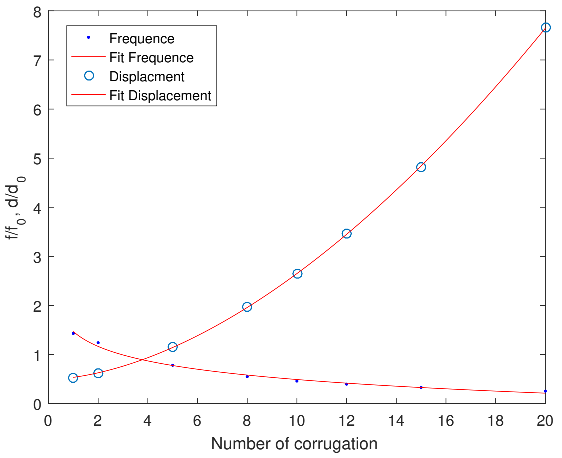

Figure 42: The influence of the number of corrugation on the natural frequency and on the limit of detection

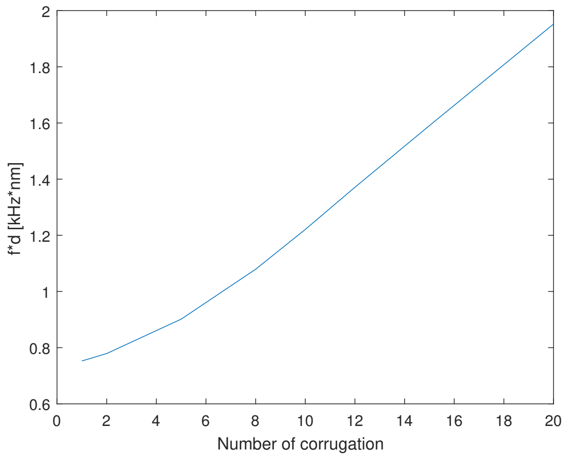

Figure 43: The influence of the number of corrugation on the factor f*d

For all the curves of the figures 38, 40 and 42 the following dimensionless function are found :

$$
\begin{aligned}
f_L(x) &= a * x^b + c = 30.52 * x^{-0.4152} - 0.7515 \\
f_n(x) &= a * x^b + c = 11.42 * x^{-0.03887} - 9.954 \\
f_p(x) &= a * x^b + c = -0.05611 * x^{0.5272} + 1.551 \\
d_p(x) &= a * x^b + c = 1.143e - 05 * x^{2.262} + 0.6319 \\
d_L(x) &= a * x^b + c = 9.323e - 07 * x^{1.994} + 0.1868 \\
d_n(x) &= a * x^b + c = 0.03994 * x^{1.732} + 0.4955
\end{aligned}
$$

That gives for the frequency f and the displacement d :

$$
\begin{aligned}
f &= f_0 * f_L(L) * f_n(n) * f_p(p) \\
d &= d_0 * d_L(L) * d_n(n) * d_p(p)
\end{aligned}
$$

This is also done for all the parameters (mainly the pre stress) involved in order to have an analytical function that gives the first natural frequency as well as the displacement for all the possible parameters and this is given in appendix.

Then it is possible to optimize the function f*d. A Matlab code of optimization is used. It is presented and described in appendix 11.4. The function 1/f*d is minimized with the fmincon Matlab function.The fmincon option allows to minimize the function with the initial value of the parameters that have to be provided under constrains that in the the frequency stay below 100 kHz and that parameters have boundaries. The needed code are presented in appendix 11.4.

Unfortunately, as this implies that the influence of all the parameters are linearly independent the found solutions is not optimal. Hence, an optimization of the direct output of the simulation is performed and presented in the next section.

8.3 Optimization

A matlab function is computed, it runs 4 Ansys codes and that returns 3 outputs : The first eigen frequency, the displacement at the fixed applied pressure (at 0.02 Pa to have the limit of detection) and the value of the pressure at which the displacement is not linear anymore (limit of linearity) given in appendix 11.3.5. This function can be just run in a matlab script with all the parameters define and gives you the 3 output. But it can also be use to produce a map of the results for all the parameters or some of them. Moreover, the Matlab function can also be used to optimize the results depending on the parameters of interest. It is going to be used to optimize only the limit of detection and the first natural frequency. The optimization code is based on the optimization of an OBJ objective function which 1/(f*d) that the matlab function particleswarm minimize. The workflow of the whole optimization process is presented in figure 44.

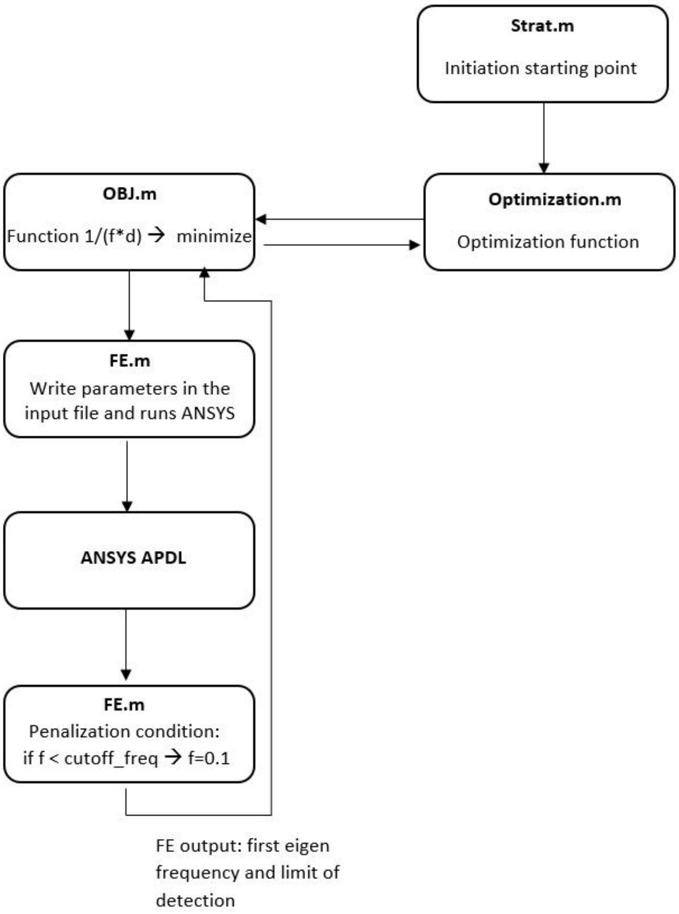

Figure 44: Optimization work flow

The first step is the script Start.m that launch the optimization by given the function to optimize and the initial parameters to the optimization function. The function OBJ, this is the function to optimize. In this case the function 1/f*d is minimized by the function optimization. f is the first eigen frequency and d the limit of detection given by the Ansys simulation. The optimization function only sent a set of parameters to the objective function which return the vector of the residues. The optimization function will then effectuate his process to minimized the residual norm without having any idea of the physical meaning of the parameters or the way the problem is solved. The function optimization that minimize with the function "particleswarm" the function OBJ presented above, by attempting to find a vector x that achieves a local minimum of the function OBJ. With parameters boundaries : minX and maxX defining a set of lower and upper bounds on the design variables, so that a solution is found in the range $minX < param < maxX$. The objective function receives the frequency and the limit of detection from the Ansys outputs. At this step a penalty condition is added, in order that if the first natural frequency output is under a specified value (100 kHz) the code assigns to it a very low value (0.1 kHz) that eliminates this candidates for the optimization. But it is important to note that for this penalty function to work the initial point have to has a natural frequency higher that the chosen cutoff frequency. All the needed matlab codes are in presented and reexplained in appendix 11.3.5. This optimization is performed for the length the number of corrugation and the position of the first corrugation and the results is given in the next section.

8.4 Final solution

The optimize design have the following parameters :

- Length : 1 mm
- Thickness : 50 nm
- Number of corrugation : 2
- Height of the corrugation : 5 μm
- Width of the corrugation : 10 μm
- Pre stress of the SiN : 50 MPa
- Pre stress of the Aluminim: -100 MPa
- Radius of the aluminun region : 25 μm
- Thickness of the aluminun region : 30 nm
- Position of the first corrugation : 29 μm
- Space between two corrugations : 5 μm

The results found are :

- First natural frequency : 100.1 kHz
- Deflection at 0.02 Pa : 0.54 nm
- Limit of linearity : 94.3 Pa.

The figure 45 present the final design modelisation. The figure 46 present the deflection in function of the applied pressure until a pressure of 200 Pa the linear curve represent a linear regression of the 3 first value when the data simulation curve has a relative difference higher than 2% from this curve it gives the pressure limit of non linearity.

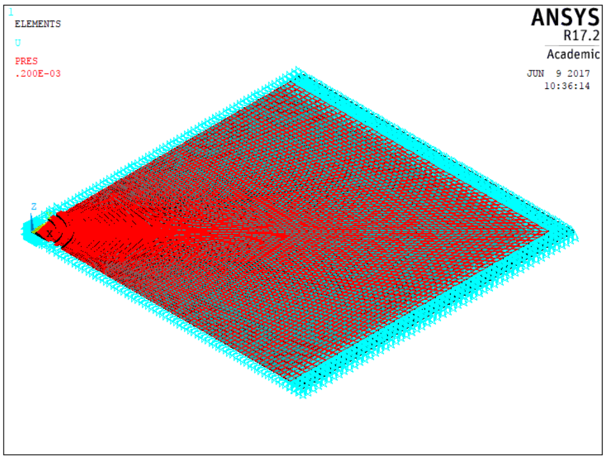

Figure 45: Final design

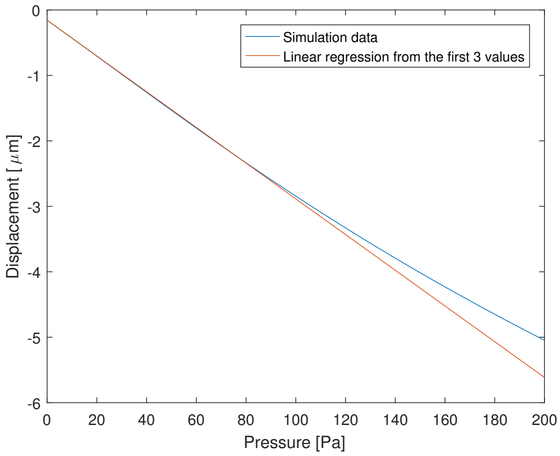

Figure 46: Deflection in function of pressure

And finally the figures 47 and 48 respectively present the colors plots of the displacement and the first natural frequency for the final design.

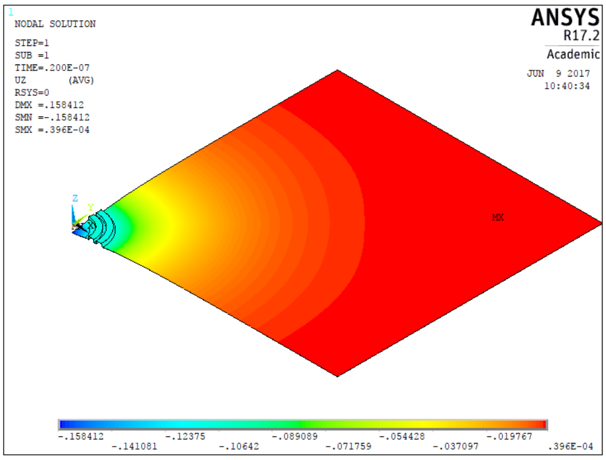

Figure 47: Color plot of the final simulation displacement

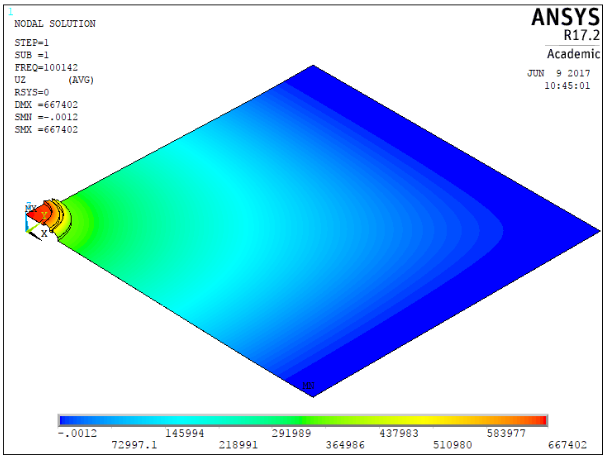

Figure 48: Color plot of the final simulation of the first natural frequency

8.5 Final solution : With aluminum all along the membrane

As for the fabrication it is easier to have an aluminum layer all along the membrane an other Ansys code is developed. But in order to do so two methods are used, the first one consist on having two solids layers with different materials, unfortunately the results do not converge meaning that the results are not reliable. The codes for the modal and the static analysis are still in appendix 11.5. The results with the same final parameters and final mesh is still performed.

With the parameters fixed :

- Length : 1 mm
- Position of the first corrugation : 29 μm
- Prestress : 50 MPa
- Height of the corrugation : 5 μm
- Width of the corrugation : 10 μm

- Space between two corrugations : 5 μm
- Thickness of SiN: 50 nm
- Height of the corrugation : 5 μm
- Width of the corrugation : 10 μm
- Pre stress of the Aluminim: -100 MPa
- Thickness of the aluminun region : 30 nm
- Space between two corrugations : 5 μm
- Number of corrugations : 2

Gives the following results :

- First natural frequency : 100 kHz
- Deflection at 0.02 Pa : 0.4 nm
- Limit of linearity : 113 Pa

But as this codes is provide by an approximation and given that all the study are not as complete as the previous one this results should be taken carefully and the first solution should be preferred. The second method is to perform and homogenization of the material with respect to their thickness with a law of mixture in parallel given the following general properties :

- Young's modulus : 123 GPa
- Density : 3046 kg/m^3
- Poisson's coefficient : 0.275

But the results are not consistent and more studies must be performed if this solution is wanted.

9 Conclusion

Many ameliorations could be performed and an analytical development should be interesting to developed in order to compared with the FE analysis. In conclusion, a design that fulfill all the specification have been provided but a fabrication facilities could be investigated. Moreover, an APDL modulate Modal ans static codes and a matlab optimization code for corrugated membranes is now available for further design for other devices. Moreover the results found are in adequacy with the one in the literature.

10 Bibliography

References

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11 Appendix

11.1 Simple membrane of SiN

11.1.1 Shell modelisation : Modal analysis

Modular parameters :

- Length: l
- Thickness: t
- Prestress applied : stress

```
FINISH
/CLEAR

/UNITS,uMKS

anchor=25
t=50e-3
l=1e3
w=1e3
stress=50

/PREP7

MP, EX, 1, 200e3
MP, NUXY,1,0.25
MP,DENS,1,3300e-18


K,001,0            ,0    ,0
K,002,L/2-anchor,0           ,0
K,003,L/2          ,0           ,0


K,011,0             ,w/2-anchor,0
K,012,L/2-anchor  ,w/2-anchor,0
K,013,L/2           ,w/2-anchor,0

K,021,0             ,w/2     ,0
K,022,L/2-anchor  ,w/2     ,0
K,023,L/2           ,w/2     ,0

/vup,1,z
/VIEW,1,1,-1,1
/PNUM,KP,1
KPLOT

*DO,j,0,10,10
*DO,i,0,1,1
A,1+i+j,2+i+j,12+i+j,11+i+j
*ENDDO
*ENDDO
APLOT

ET,1,SHELL281
```

```
SECTYPE,1,SHELL,,SCT1
SECDATA,t,1,0,9
SECOFFSET,bottom

ARSYM,Y,ALL
NUMMRG,ALL,1e-9

ARSYM,X,ALL
NUMMRG,ALL,1e-9


aadd,1,5,9,13
aadd,2,3,4,6,7,8,10,11,12,14,15,16

MAT,1
TYPE,1

ESIZE,10
ASEL,S,AREA,,1
ASEL,A,AREA,,17
AATT,1,,1
AMESH,ALL

ALLSEL,ALL


ASEL,S,AREA,,1
NSLA,S,1
D,ALL,ALL,0
ALLSEL,ALL,ALL

INISTATE,SET,MAT,1
INISTATE,DEFINE,,,,,stress,stress
ALLSEL,ALL,ALL

FINISH
/SOLU
ANTYPE,STATIC,NEW    ! Static analysis
PSTRESS,ON
SOLVE
FINISH

/POST1
/DSCALE,ALL,1
/CONTOUR,ALL,128
PLNSOL,U,Z
FINISH

/SOL
ANTYPE,MODAL         ! Modal analysis
MODOPT,LANB,5,1e4
MXPAND,5
PSTRESS,ON
SOLVE
```

```
FINISH

/POST1
/DSCALE,ALL,AUTO
/CONTOUR,ALL,128
SET,FIRST
```

11.1.2 Shell modelisation : Static analysis

Modular parameters :

- Length : l
- Thickness: t
- Prestress: stress
- Applied pressure: press
- Number of pressure step: nb

```
FINISH
/CLEAR

/UNITS,uMKS

anchor=25
t=50e-3
l=1e3
w=1e3
stress=50
press=20e-6
nb =200 ! Number of pressure step

/PREP7

MP, EX, 1, 200e3
MP, NUXY,1,0.25
MP,DENS,1,3300e-18



K,001,0          ,0         ,0
K,002,L/2-anchor ,0         ,0
K,003,L/2        ,0         ,0


K,011,0          ,w/2-anchor        ,0
K,012,L/2-anchor ,w/2-anchor        ,0
K,013,L/2        ,w/2-anchor        ,0

K,021,0          ,w/2       ,0
K,022,L/2-anchor ,w/2       ,0
K,023,L/2        ,w/2       ,0

/vup,1,z
/VIEW,1,1,-1,1
/PNUM,KP,1
KPLOT

*DO,j,0,10,10
*DO,i,0,1,1
A,1+i+j,2+i+j,12+i+j,11+i+j
*ENDDO
*ENDDO
APLOT
```

```
ET,1,SHELL281
SECTYPE,1,SHELL,,SCT1
SECDATA,t,1,0,9
SECOFFSET,bottom

ARSYM,Y,ALL
NUMMRG,ALL,1e-9

ARSYM,X,ALL
NUMMRG,ALL,1e-9


aadd,1,5,9,13
aadd,2,3,4,6,7,8,10,11,12,14,15,16

MAT,1
TYPE,1

ESIZE,W/300
ASEL,S,AREA,,1
ASEL,A,AREA,,17
AATT,1,,1
AMESH,ALL

ALLSEL,ALL

ASEL,S,AREA,,1
NSLA,S,1
D,ALL,ALL,0
ALLSEL,ALL,ALL

INISTATE,SET,MAT,1
INISTATE,DEFINE,,,,,stress ,stress
ALLSEL,ALL,ALL

ASEL,S,AREA,,17
NSLA,S,1
SF,ALL,PRES, press

ALLSEL,ALL,ALL

/SOLU

ANTYPE,STATIC,NEW
NLGEOM,ON
NCNV,,1E20
KBC,0
TIME,press
nm=node(0,0,0)
MONITOR,1,nm,uz
OUTRES,all ,all
NSUBST,nb,400,nb
SOLVE
```

```
FINISH

/POST26
NSOL,2 ,nm,U,Z
/axlab ,y, Displacement  (um)
/AXLAB,x, Pressure  (Pa)
PLVAR,2
FINISH
```

11.1.3 Solid modelisation : Modal analysis

Modular parameters :
- Length: l
- Thickness: t
- Prestress: stress

```
FINISH
/CLEAR

/UNITS,uMKS

*SET,anchor,25
*SET,t,50e-3
*SET,l,1e3
*SET,stress,50

/PREP7

MP,EX,1,200e3
MP,NUXY,1,0.25
MP,DENS,1,3300e-18

K,001,0                       ,0                   ,0
K,002,L/2                     ,0                   ,0
K,003,L/2+anchor,0                      ,0

K,011,0                       ,L/2      ,0
K,012,L/2                     ,L/2      ,0
K,013,L/2+anchor,L/2          ,0

K,021,0                       ,L/2+anchor          ,0
K,022,L/2                     ,L/2+anchor          ,0
K,023,L/2+anchor,L/2+anchor             ,0

K,101,0                       ,0        ,t
K,102,L/2                     ,0        ,t
K,103,L/2+anchor,0            ,t

K,111,0                       ,L/2      ,t
K,112,L/2                     ,L/2      ,t
K,113,L/2+anchor,L/2          ,t

K,121,0                       ,L/2+anchor          ,t
K,122,L/2                     ,L/2+anchor          ,t
K,123,L/2+anchor,L/2+anchor             ,t

/vup,1,z
/VIEW,1,1,-1,1
/PNUM,KP,1
KPLOT

*DO,k,0,000,100
*DO,j,0,10,10
```

```
*DO,i,0,1,1
V,1+i+j+k,2+i+j+k,12+i+j+k,11+i+j+k,101+i+j+k,102+i+j+k,112+i+j+k,111+i+j+kvplot
*ENDDO
*ENDDO
*ENDDO
VPLOT

NUMMRG,KP,1E-3
/PNUM,VOLU,1
VPLOT

ET,1,SOLID185
KEYOPT,1,2,2
ESIZE,5
TYPE,1
SECNUM,1
MAT,1
VMESH,ALL

NUMMRG,NODE,1e-3

INISTATE,SET,MAT,1
INISTATE,DEFINE,,,,,stress,stress
ALLSEL,ALL,ALL

ASEL,S,AREA,,7
ASEL,A,AREA,,17
ASEL,A,AREA,,12
NSLA,S,1
D,ALL,ALL,0
ALLSEL,ALL,ALL

NSEL,S,LOC,X,0,L/2
NSEL,R,LOC,Y,0,0
NSEL,R,LOC,Z,0,t
D,ALL,UY,0
ALLSEL,ALL,ALL

NSEL,S,LOC,Y,0,L/2
NSEL,R,LOC,X,0,0
NSEL,R,LOC,Z,0,t
D,ALL,UX,0
ALLSEL,ALL,ALL

FINISH
/SOLU
ANTYPE,STATIC,NEW   ! Static analysis
PSTRESS,ON
SOLVE
FINISH

/POST1
/DSCALE,ALL,1
/CONTOUR,ALL,128
```

```
PLNSOL,U,Z
FINISH

/SOL
ANTYPE,MODAL              ! Modal analysis
MODOPT,LANB,5,1e4
MXPAND,5
PSTRESS,ON
SOLVE
FINISH

/POST1
/DSCALE,ALL,AUTO
/CONTOUR,ALL,128
SET,FIRST
```

11.1.4 Solid modelisation : Static Analysis

Modular parameters :

- Length:l
- Thickness: t
- Prestress: stress
- Applied pressure: press
- Number of pressure step: nb

```
FINISH
/CLEAR

/UNITS,uMKS

*SET,anchor,25
*SET,t,50e-3
*SET,l,0.95e3
*SET,stress,50
*SET,press,20E-6
nb=200

/PREP7

MP,EX,1,200e3
MP,NUXY,1,0.25
MP,DENS,1,3300e-18


K,001,0                    ,0                 ,0
K,002,L/2                  ,0                 ,0
K,003,L/2+anchor,0                   ,0

K,011,0                    ,L/2               ,0
K,012,L/2                  ,L/2               ,0
K,013,L/2+anchor,L/2                 ,0

K,021,0                    ,L/2+anchor        ,0
K,022,L/2                  ,L/2+anchor        ,0
K,023,L/2+anchor,L/2+anchor          ,0

K,101,0                    ,0                 ,t
K,102,L/2                  ,0                 ,t
K,103,L/2+anchor,0                   ,t

K,111,0                    ,L/2               ,t
K,112,L/2                  ,L/2               ,t
K,113,L/2+anchor,L/2                 ,t

K,121,0                    ,L/2+anchor        ,t
K,122,L/2                  ,L/2+anchor        ,t
K,123,L/2+anchor,L/2+anchor          ,t

/vup,1,z
/VIEW,1,1,-1,1
```

```
/PNUM,KP,1
KPLOT

*DO,k,0,000,100
*DO,j,0,10,10
*DO,i,0,1,1
V,1+i+j+k,2+i+j+k,12+i+j+k,11+i+j+k,
101+i+j+k,102+i+j+k,112+i+j+k,111+i+j+kvplot,
*ENDDO
*ENDDO
*ENDDO
VPLOT

NUMMRG,KP,1E-3
/PNUM,VOLU,1
VPLOT

ET,1,SOLID185
KEYOPT,1,2,2
ESIZE,11
SECNUM,1
MAT,1
VMESH,ALL

NUMMRG,NODE,1e-3

INISTATE,SET,MAT,1
INISTATE,DEFINE,,,,,stress,stress
ALLSEL,ALL,ALL

ASEL,S,AREA,,7
ASEL,A,AREA,,17
ASEL,A,AREA,,12
NSLA,S,1
D,ALL,ALL,0
ALLSEL,ALL,ALL

ASEL,S,AREA,,6
NSLA,S,1
SF,ALL,PRES,press

NSEL,S,LOC,X,0,L/2
NSEL,R,LOC,Y,0,0
NSEL,R,LOC,Z,0,t+tg+h
D,ALL,UY,0
ALLSEL,ALL,ALL

NSEL,S,LOC,Y,0,L/2
NSEL,R,LOC,X,0,0
NSEL,R,LOC,Z,0,t+tg+h
D,ALL,UX,0
ALLSEL,ALL,ALL

FINISH
```

```
/SOL
ANTYPE,STATIC,NEW
NLGEOM,ON
NCNV,,1E20
KBC,0
TIME,press
*SET,nm,node(0,0,0)
MONITOR,1,nm,uz
OUTRES,all,all
NSUBST,nb,400,nb
SOLVE
FINISH

/POST26
NSOL,2,nm,U,Z
/axlab,y,Displacement (um)
/AXLAB,x,Pressure (Pa)
PLVAR,2
FINISH
```

11.2 Reflective bi material membrane

11.2.1 Shell modelisation : Modal Analysis

Modular parameters :

- Length:l
- Thickness: t
- Prestress of the SiN: stress
- Prestress of the reflective region material: stress2
- Thickness of the reflective region: tg
- Radius of the reflective region: r
- Material used for the reflective region

```
FINISH
/CLEAR

/UNITS,uMKS

*SET,anchor,25
*SET,t,50e-3
*SET,tg,30e-3
*SET,l,1e3
*SET,stress,150
*SET,press,20e-6
*SET,stress2,-100
r=375

/PREP7
MP, EX, 1, 200e3
MP, NUXY,1,0.25
MP,DENS,1,3300e-18

MP, EX, 2, 78e3   ! Gold
MP, NUXY,2,0.42
MP,DENS,2,19300e-18

!MP, EX, 2, 75e3 ! Alu
!MP, NUXY,2,0.33
!MP,DENS,2,2700e-18

K,001,0    ,0  ,0
K,002,L/2-anchor ,0  ,0
K,003,L/2    ,0  ,0
K,011,0    ,w/2-anchor  ,0
K,012,L/2-anchor    ,w/2-anchor  ,0
K,013,L/2    ,w/2-anchor  ,0
K,021,0    ,w/2  ,0
K,022,L/2-anchor    ,w/2  ,0
K,023,L/2    ,w/2  ,0

/vup,1,z
/VIEW,1,1,-1,1
/PNUM,KP,1
KPLOT
```

```
*DO, j ,0 ,10 ,10
*DO, i ,0 ,1 ,1
A,1+ i+j ,2+ i+j ,12+ i+j ,11+ i+j
*ENDDO
*ENDDO

APLOT

ET, 1 ,SHELL281
SECTYPE, 1 ,SHELL, ,SCT1
SECDATA, t ,1 ,0 ,9
SECOFFSET, bot

CYL4,0 ,0 ,0 ,0 ,r ,90
aadd ,2 ,3 ,4
APTN, 1 ,5
AGLUE, 2 ,3
ALLSEL, ALL

ESIZE ,20
ASEL, S ,AREA, ,6
ASEL, A, AREA, ,3
MAT, 1
secnum ,1
TYPE, 1
AATT, 1 , ,1
AMESH, ALL
ALLSEL, ALL

ET, 2 ,SHELL281
KEYOPT, 2 ,1 ,0
KEYOPT, 2 ,8 ,1
KEYOPT, 2 ,9 ,0
SECTYPE, 2 ,SHELL, ,SCT2
secdata ,  tg ,2 ,0.0 ,3
secdata ,  t ,1 ,0.0 ,3
SECOFFSET, bot

ESIZE ,20
ASEL, S ,AREA, ,2
TYPE, 2
secnum ,2
AMESH, ALL
ALLSEL, ALL

INISTATE, SET ,MAT, 1
INISTATE, DEFINE, , , , , stress , stress
ALLSEL, ALL, ALL

INISTATE, SET ,MAT, 2
INISTATE, DEFINE, , , , , stress2 , stress2
ALLSEL, ALL, ALL
```

```
ASEL,S,AREA,,6
NSLA,S,1
D,ALL,ALL,0
ALLSEL,ALL,ALL

NSEL,S,LOC,X,0,L/2
NSEL,R,LOC,Y,0,0
D,ALL,UY,0,,,,ROTZ,ROTX
ALLSEL,ALL,ALL

NSEL,S,LOC,Y,0,L/2
NSEL,R,LOC,X,0,0
D,ALL,UX,0,,,,ROTZ,ROTY
ALLSEL,ALL,ALL

FINISH

/SOLU
ANTYPE,STATIC,NEW    ! Static analysis
PSTRESS,ON
SOLVE
FINISH

/POST1
/DSCALE,ALL,1
/CONTOUR,ALL,128
PLNSOL,U,Z

/SOLU
ANTYPE,MODAL         ! Modal analysis
MODOPT,LANB,5,1e4
MXPAND,5
PSTRESS,ON
SOLVE
FINISH

/POST1
/DSCALE,ALL,AUTO
/CONTOUR,ALL,128
SET,FIRST
PLNSOL,U,Z
```

11.2.2 Shell modelisation : Static Analysis

Modular parameters :

- Length: l
- Thickness: t
- Prestress of the SiN: stress
- Applied pressure: press
- Number of pressure step: nb
- Prestress of the reflective region material: stress2
- Thickness of the reflective region: tg
- Radius of the reflective region: r
- Material used for the reflective region

```
FINISH
/CLEAR

/UNITS,uMKS

*SET,anchor,25
*SET,t,50e-3
*SET,tg,30e-3
*SET,l,1e3
*SET,w,1e3
*SET,stress,150
*SET,press,20e-6
*SET,stress2,-100
r=375
nb=200

/PREP7
MP, EX, 1, 200e3
MP, NUXY,1,0.25
MP,DENS,1,3300e-18

MP, EX, 2, 78e3
MP, NUXY,2,0.42
MP,DENS,2,19300e-18

!MP, EX, 2, 75e3
!MP, NUXY,2,0.33
!MP,DENS,2,2700e-18

K,001,0    ,0  ,0
K,002,L/2-anchor  ,0  ,0
K,003,L/2    ,0  ,0
K,011,0    ,w/2-anchor  ,0
K,012,L/2-anchor    ,w/2-anchor  ,0
K,013,L/2    ,w/2-anchor  ,0
K,021,0    ,w/2  ,0
K,022,L/2-anchor    ,w/2  ,0
K,023,L/2    ,w/2  ,0

/vup,1,z
/VIEW,1,1,-1,1
```

```
/PNUM,KP,1
KPLOT

*DO,j,0,10,10
*DO,i,0,1,1
A,1+i+j,2+i+j,12+i+j,11+i+j
*ENDDO
*ENDDO

APLOT

ET,1,SHELL281
SECTYPE,1,SHELL,,SCT1
SECDATA,t,1,0,9
SECOFFSET,bot

CYL4,0,0,0,0,r,90
aadd,2,3,4
APTN,1,5
AGLUE,2,3
ALLSEL,ALL

ESIZE,3
ASEL,S,AREA,,6
ASEL,A,AREA,,3
MAT,1
secnum,1
TYPE,1
AATT,1,,1
AMESH,ALL
ALLSEL,ALL

ET,2,SHELL281
KEYOPT,2,1,0
KEYOPT,2,8,1
KEYOPT,2,9,0
SECTYPE,2,SHELL,,SCT2
secdata, tg,2,0.0,3
secdata, t,1,0.0,3
SECOFFSET,mid

ESIZE,20
ASEL,S,AREA,,2
TYPE,2
secnum,2
AMESH,ALL
ALLSEL,ALL

INISTATE,SET,MAT,1
INISTATE,DEFINE,,,,,stress,stress
ALLSEL,ALL,ALL

INISTATE,SET,MAT,2
INISTATE,DEFINE,,,,,stress2,stress2
```

```
ALLSEL,ALL,ALL

ASEL,S,AREA,,6
NSLA,S,1
D,ALL,ALL,0
ALLSEL,ALL,ALL

ASEL,S,AREA,,2,3
NSLA,S,1
SF,ALL,PRES, press
ALLSEL,ALL,ALL

NSEL,S,LOC,X,0,L/2
NSEL,R,LOC,Y,0,0
D,ALL,UY,0,,,,ROTZ,ROTX
ALLSEL,ALL,ALL

NSEL,S,LOC,Y,0,L/2
NSEL,R,LOC,X,0,0
D,ALL,UX,0,,,,ROTZ,ROTY
ALLSEL,ALL,ALL

FINISH
/SOL
ANTYPE,STATIC,NEW                  ! Static analysis
NLGEOM,ON   !non-linearities
NCNV,,1E20
KBC,0
TIME,press
*SET,nm,node(0,0,0)
MONITOR,1,nm,uz
OUTRES,all,all !write the result at every step
NSUBST,nb,400,nb
SOLVE
FINISH

/POST26
NSOL,2,nm,U,Z
/axlab,y,Displacement (um)
/AXLAB,x,Pressure (Pa)
PLVAR,2
FINISH
```

11.2.3 Solid modelisation : Modal Analysis

- Length:l
- Thickness :t
- Prestress of the SiN: stress
- Prestress of the reflective region material: stress2
- Thickness of the reflective region: tg
- Radius of the reflective region: r
- Material used for the reflective region

```
FINISH
/CLEAR

/UNITS,uMKS

*SET,anchor,25
*SET,t,50e-3
*SET,tg,30e-3
*SET,l,1e3
*SET,stress,450
*SET,press,20E-6
*SET,stress2,-100
r=250


/PREP7

MP,EX,1,200e3
MP,NUXY,1,0.25
MP,DENS,1,3300e-18

/CHOiCE :GOLD/ALU
MP, EX, 2, 75e3
MP, NUXY,2,0.33
MP,DENS,2,2700e-18

!MP, EX, 2, 78e3
!MP, NUXY,2,0.42
!MP,DENS,2,19300e-18


K,001,0                   ,0                 ,0
K,002,L/2                 ,0                 ,0
K,003,L/2+anchor          ,0                 ,0

K,011,0                   ,L/2               ,0
K,012,L/2                 ,L/2               ,0
K,013,L/2+anchor          ,L/2               ,0

K,021,0                   ,L/2+anchor        ,0
K,022,L/2                 ,L/2+anchor        ,0
K,023,L/2+anchor          ,L/2+anchor        ,0

K,101,0                   ,0                 ,t
```

```
K,102,L/2             ,0              ,t
K,103,L/2+anchor      ,0              ,t

K,111,0               ,L/2            ,t
K,112,L/2             ,L/2            ,t
K,113,L/2+anchor      ,L/2            ,t

K,121,0               ,L/2+anchor     ,t
K,122,L/2             ,L/2+anchor     ,t
K,123,L/2+anchor      ,L/2+anchor     ,t


/vup,1,z
/VIEW,1,1,-1,1
/PNUM,KP,1
KPLOT

*DO,k,0,000,100
*DO,j,0,10,10
*DO,i,0,1,1
V,1+i+j+k,2+i+j+k,12+i+j+k,11+i+j+k,101+i+j+k,102+i+j+k,112+i+j+k,111+i+j+kvplot
*ENDDO
*ENDDO
*ENDDO
VPLOT

CYL4,0,0,0,0,r,90,tg+t
VSBV,1,5
CYLIND,0,r,0,t,0,90
CYLIND,0,r,0,-tg,0,90
ALLSEL,ALL
VGLUE,5,1

K,200,l/2,l/2,t
K,201,l/2,L/2,-tg

A,16,15,200,201
VSEL,S,VOLU,,1
VSEL,A,VOLU,,6,7
VSBA,ALL,23
ALLSEL,ALL

NUMMRG,KP,1E-3
/PNUM,VOLU,1
VPLOT


ET,1,SOLID185,
KEYOPT,1,2,2
MOPT,TRANS,1.2
MOPT,SPLIT,2

ESIZE,7
VSEL,S,VOLU,,2,5
```

```
VSEL,A,VOLU,,8
VSEL,A,VOLU,,11,12
TYPE,1
SECNUM,1
MAT,1
VMESH,ALL
ALLSEL,ALL


ET,2,SOLID185
KEYOPT,2,2,2
VSEL,S,VOLU,,9,10
MAT,2
TYPE,2
SECNUM,2
VMESH,ALL
ALLSEL,ALL

NUMMRG,NODE,1e-3

INISTATE,SET,MAT,1
INISTATE,DEFINE,,,,,stress,stress
ALLSEL,ALL,ALL
INISTATE,SET,MAT,2
INISTATE,DEFINE,,,,,stress2,stress2
ALLSEL,ALL,ALL

ASEL,S,AREA,,7
ASEL,A,AREA,,17
ASEL,A,AREA,,12
NSLA,S,1
D,ALL,ALL,0
ALLSEL,ALL,ALL

NSEL,S,LOC,X,0,L/2
NSEL,R,LOC,Y,0,0
NSEL,R,LOC,Z,-tg,t
D,ALL,UY,0
ALLSEL,ALL,ALL

NSEL,S,LOC,Y,0,L/2
NSEL,R,LOC,X,0,0
NSEL,R,LOC,Z,-tg,t
D,ALL,UX,0
ALLSEL,ALL,ALL

FINISH
/SOLU
ANTYPE,STATIC,NEW    ! Static analysis
PSTRESS,ON
SOLVE
FINISH

/POST1
```

```
/DSCALE,ALL,1
/CONTOUR,ALL,128
PLNSOL,U,Z
FINISH

/SOL
ANTYPE,MODAL          ! Modal analysis
MODOPT,LANB,5,1e4
MXPAND,5
PSTRESS,ON
SOLVE
FINISH

/POST1
/DSCALE,ALL,AUTO
/CONTOUR,ALL,128
SET,FIRST
```

11.2.4 Solid modelisation : Static Analysis

Modular parameters

- Length: L
- Thickness: t
- Prestress of the SiN: stress
- Applied pressure: press
- Number of pressure step: nb
- Prestress of the reflective region material: stress2
- Thickness of the reflective region: tg
- Radius of the reflective region:r
- Material used for the reflective region

```
FINISH
/CLEAR

/UNITS,uMKS

*SET,anchor,25
*SET,t,50e-3
*SET,tg,30e-3
*SET,l,1e3
*SET,l,1e3
*SET,stress,50
*SET,press,20E-6
*SET,stress2,-100
r=100
nb=200
/PREP7

MP,EX,1,200e3
MP,NUXY,1,0.25
MP,DENS,1,3300e-18

MP, EX, 2, 75e3
MP, NUXY,2,0.33
MP,DENS,2,2700e-18

!MP, EX, 2, 78e3
!MP, NUXY,2,0.42
!MP,DENS,2,19300e-18

K,001,0              ,0              ,0
K,002,L/2            ,0              ,0
K,003,L/2+anchor     ,0              ,0

K,011,0              ,L/2            ,0
K,012,L/2            ,L/2            ,0
K,013,L/2+anchor     ,L/2            ,0

K,021,0              ,L/2+anchor     ,0
K,022,L/2            ,L/2+anchor     ,0
K,023,L/2+anchor     ,L/2+anchor     ,0
```

```
K,101,0                 ,0              ,t
K,102,L/2               ,0              ,t
K,103,L/2+anchor        ,0              ,t

K,111,0                 ,L/2            ,t
K,112,L/2               ,L/2            ,t
K,113,L/2+anchor        ,L/2            ,t

K,121,0                 ,L/2+anchor     ,t
K,122,L/2               ,L/2+anchor     ,t
K,123,L/2+anchor        ,L/2+anchor     ,t


/vup,1,z
/VIEW,1,1,-1,1
/PNUM,KP,1
KPLOT

*DO,k,0,000,100
*DO,j,0,10,10
*DO,i,0,1,1
V,1+i+j+k,2+i+j+k,12+i+j+k,11+i+j+k,101+i+j+k,102+i+j+k,112+i+j+k,111+i+j+kvplot
*ENDDO
*ENDDO
*ENDDO
VPLOT


CYL4,0,0,0,0,r,90,tg+t
VSBV,1,5
CYLIND,0,r,0,t,0,90
CYLIND,0,r,0,-tg,0,90
ALLSEL,ALL
VGLUE,5,1

K,200,l/2,l/2,t
K,201,l/2,L/2,-tg

A,16,15,200,201
VSEL,S,VOLU,,1
VSEL,A,VOLU,,6,7
VSBA,ALL,23
ALLSEL,ALL

NUMMRG,KP,1E-3
/PNUM,VOLU,1
VPLOT


ET,1,SOLID185
KEYOPT,1,2,2
MOPT,TRANS,1.2
MOPT,SPLIT,2
```

```
ESIZE,7
VSEL,S,VOLU,,2,5
VSEL,A,VOLU,,8
VSEL,A,VOLU,,11,12
TYPE,1
SECNUM,1
MAT,1
VMESH,ALL
ALLSEL,ALL


ET,2,SOLID185
KEYOPT,2,2,2
VSEL,S,VOLU,,9,10
MAT,2
TYPE,2
SECNUM,2
VMESH,ALL
ALLSEL,ALL

NUMMRG,NODE,1e-3

INISTATE,SET,MAT,1
INISTATE,DEFINE,,,,,stress,stress
ALLSEL,ALL,ALL
INISTATE,SET,MAT,2
INISTATE,DEFINE,,,,,stress2,stress2
ALLSEL,ALL,ALL

ASEL,S,AREA,,7
ASEL,A,AREA,,17
ASEL,A,AREA,,12
NSLA,S,1
D,ALL,ALL,0
ALLSEL,ALL,ALL

NSEL,S,LOC,X,0,L/2
NSEL,R,LOC,Y,0,L/2
NSEL,R,LOC,Z,t,t
SF,ALL,PRES,press


NSEL,S,LOC,X,0,L/2
NSEL,R,LOC,Y,0,0
NSEL,R,LOC,Z,-tg,t
D,ALL,UY,0
ALLSEL,ALL,ALL


NSEL,S,LOC,Y,0,L/2
NSEL,R,LOC,X,0,0
NSEL,R,LOC,Z,-tg,t
D,ALL,UX,0
ALLSEL,ALL,ALL
```

```
FINISH
/SOL
ANTYPE,STATIC,NEW                     ! Static analysis
NLGEOM,ON
NCNV,,1E20
KBC,0
TIME,press
*SET,nm,node(0,0,0)
MONITOR,1,nm,uz
OUTRES,all,all
NSUBST,nb,400,nb
SOLVE
FINISH

/POST26
NSOL,2,nm,U,Z
/axlab,y,Displacement (um)
/AXLAB,x,Pressure (Pa)
PLVAR,2
FINISH
```

11.2.5 Solid modelisation : Modal analysis with reflective region on all the membrane

Modular parameters

- Length: L
- Thickness: t
- Prestress of the SiN: stress
- Prestress of the reflective region material: stress2
- Thickness of the reflective region: tg
- Material used for the reflective region

```
FINISH
/CLEAR

/UNITS,uMKS

*SET,anchor,25
*SET,t,50e-3
*SET,tg,30e-3
*SET,l,1e3
*SET,stress,50
*SET,press,20E-6
*SET,stress2,-100
r=325

/PREP7


MP,EX,1,200e3
MP,NUXY,1,0.25
MP,DENS,1,3300e-18

MP,  EX,  2,  75e3
MP,  NUXY,2,0.33
MP,DENS,2,2700e-18

!MP,  EX,  2,  78e3
!MP,  NUXY,2,0.42
!MP,DENS,2,19300e-18


K,001,0              ,0                ,0
K,002,L/2            ,0                ,0
K,003,L/2+anchor     ,0                ,0

K,011,0              ,L/2              ,0
K,012,L/2            ,L/2              ,0
K,013,L/2+anchor     ,L/2              ,0

K,021,0              ,L/2+anchor       ,0
K,022,L/2            ,L/2+anchor       ,0
K,023,L/2+anchor     ,L/2+anchor       ,0

K,101,0              ,0                ,t
K,102,L/2            ,0                ,t
```

```
K,103,L/2+anchor        ,0              ,t

K,111,0                 ,L/2            ,t
K,112,L/2               ,L/2            ,t
K,113,L/2+anchor        ,L/2            ,t

K,121,0                 ,L/2+anchor     ,t
K,122,L/2               ,L/2+anchor     ,t
K,123,L/2+anchor        ,L/2+anchor     ,t


K,201,0                 ,0              ,0
K,202,L/2               ,0              ,0
K,203,L/2               ,L/2            ,0
K,204,0                 ,L/2            ,0

K,205,0                 ,0              ,-tg
K,206,L/2               ,0              ,-tg
K,207,L/2               ,L/2            ,-tg
K,208,0                 ,L/2            ,-tg


/vup,1,z
/VIEW,1,1,-1,1
/PNUM,KP,1
KPLOT

*DO,k,0,000,100
*DO,j,0,10,10
*DO,i,0,1,1
V,1+i+j+k,2+i+j+k,12+i+j+k,11+i+j+k,101+i+j+k,102+i+j+k,112+i+j+k,111+i+j+kvplot
*ENDDO
*ENDDO
*ENDDO
VPLOT

V,201,202,203,204,205,206,207,208
VGLUE,ALL

NUMMRG,KP,1E-3
/PNUM,VOLU,1
VPLOT

ET,1,SOLID185
KEYOPT,1,2,2
ESIZE,10
VSEL,S,VOLU,,1,4
TYPE,1
SECNUM,1
MAT,1
VMESH,ALL
ALLSEL,ALL

ET,2,SOLID185
```

```
KEYOPT,2,2,2
ESIZE,10
VSEL,S,VOLU,,6
TYPE,2
SECNUM,2
MAT,2
VMESH,ALL
ALLSEL,ALL

NUMMRG,NODE,1e-3

INISTATE,SET,MAT,1
INISTATE,DEFINE,,,,,stress,stress
ALLSEL,ALL,ALL

INISTATE,SET,MAT,2
INISTATE,DEFINE,,,,,stress2,stress2
ALLSEL,ALL,ALL


ASEL,S,AREA,,7
ASEL,A,AREA,,17
ASEL,A,AREA,,12
NSLA,S,1
D,ALL,ALL,0
ALLSEL,ALL,ALL


NSEL,S,LOC,X,0,L/2
NSEL,R,LOC,Y,0,0
NSEL,R,LOC,Z,-tg,t
D,ALL,UY,0
ALLSEL,ALL,ALL


NSEL,S,LOC,Y,0,L/2
NSEL,R,LOC,X,0,0
NSEL,R,LOC,Z,-tg,t
D,ALL,UX,0
ALLSEL,ALL,ALL

FINISH
/SOLU
ANTYPE,STATIC,NEW   ! Static analysis
PSTRESS,ON
SOLVE
FINISH

/POST1
/DSCALE,ALL,1
/CONTOUR,ALL,128
PLNSOL,U,Z
FINISH
```

```
/SOL
ANTYPE,MODAL             ! Modal analysis
MODOPT,LANB,5 ,1e4
MXPAND,5
PSTRESS,ON
SOLVE
FINISH

/POST1
/DSCALE,ALL,AUTO
/CONTOUR,ALL,128
SET,FIRST
```

11.2.6 Solid modelisation : Static analysis with reflective region on all the membrane

Modular parameters
- Length: L
- Thickness: t
- Prestress of the SiN: stress
- Applied pressure: press
- Number of pressure step: nb
- Prestress of the reflective region material: stress2
- Thickness of the reflective region: tg
- Material used for the reflective region

```
FINISH
/CLEAR

/UNITS,uMKS

*SET, anchor ,25
*SET, t ,50e-3
*SET, tg ,30e-3
*SET, l ,1e3
*SET, stress ,50
*SET, press ,20E-6
*SET, stress2 ,-100
nb=200

/PREP7

MP,EX,1,200e3
MP,NUXY,1,0.25
MP,DENS,1,3300e-18

MP, EX, 2, 75e3
MP, NUXY,2,0.33
MP,DENS,2,2700e-18

!MP, EX, 2, 78e3
!MP, NUXY,2,0.42
!MP,DENS,2,19300e-18

K,001,0                ,0               ,0
K,002,L/2              ,0               ,0
K,003,L/2+anchor       ,0               ,0

K,011,0                ,L/2             ,0
K,012,L/2              ,L/2             ,0
K,013,L/2+anchor       ,L/2             ,0

K,021,0                ,L/2+anchor      ,0
K,022,L/2              ,L/2+anchor      ,0
K,023,L/2+anchor       ,L/2+anchor      ,0

K,101,0                ,0               ,t
K,102,L/2              ,0               ,t
```

```
K,103,L/2+anchor        ,0              ,t

K,111,0                 ,L/2            ,t
K,112,L/2               ,L/2            ,t
K,113,L/2+anchor        ,L/2            ,t

K,121,0                 ,L/2+anchor     ,t
K,122,L/2               ,L/2+anchor     ,t
K,123,L/2+anchor        ,L/2+anchor     ,t

K,201,0                 ,0              ,0
K,202,L/2               ,0              ,0
K,203,L/2               ,L/2            ,0
K,204,0                 ,L/2            ,0

K,205,0                 ,0              ,-tg
K,206,L/2               ,0              ,-tg
K,207,L/2               ,L/2            ,-tg
K,208,0                 ,L/2            ,-tg

/vup,1,z
/VIEW,1,1,-1,1
/PNUM,KP,1
KPLOT

*DO,k,0,000,100
*DO,j,0,10,10
*DO,i,0,1,1
V,1+i+j+k,2+i+j+k,12+i+j+k,11+i+j+k,
101+i+j+k,102+i+j+k,112+i+j+k,111+i+j+kvplot ,
*ENDDO
*ENDDO
*ENDDO
VPLOT

V,201,202,203,204,205,206,207,208
VGLUE,ALL

NUMMRG,KP,1E-3
/PNUM,VOLU,1
VPLOT

ET,1,SOLID185
KEYOPT,1,2,2
ESIZE,10
VSEL,S,VOLU,,1,4
TYPE,1
SECNUM,1
MAT,1
VMESH,ALL
ALLSEL,ALL

ET,2,SOLID185
KEYOPT,2,2,2
```

```
ESIZE,10
VSEL,S,VOLU,,6
TYPE,2
SECNUM,2
MAT,2
VMESH,ALL
ALLSEL,ALL

NUMMRG,NODE,1e-3

INISTATE,SET,MAT,1
INISTATE,DEFINE,,,,,stress,stress
ALLSEL,ALL,ALL

INISTATE,SET,MAT,2
INISTATE,DEFINE,,,,,stress2,stress2
ALLSEL,ALL,ALL


ASEL,S,AREA,,7
ASEL,A,AREA,,17
ASEL,A,AREA,,12
NSLA,S,1
D,ALL,ALL,0
ALLSEL,ALL,ALL

NSEL,S,LOC,X,0,L/2
NSEL,R,LOC,Y,0,L/2
NSEL,R,LOC,Z,t,t
SF,ALL,PRES,press

NSEL,S,LOC,X,0,L/2
NSEL,R,LOC,Y,0,0
NSEL,R,LOC,Z,-tg,t
D,ALL,UY,0
ALLSEL,ALL,ALL

NSEL,S,LOC,Y,0,L/2
NSEL,R,LOC,X,0,0
NSEL,R,LOC,Z,-tg,t
D,ALL,UX,0
ALLSEL,ALL,ALL

FINISH
/SOL
ANTYPE,STATIC,NEW                   ! Static analysis
NLGEOM,ON
NCNV,,1E20
KBC,0
TIME,press
*SET,nm,node(0,0,0)
MONITOR,1,nm,uz
OUTRES,all,all
NSUBST,nb,400,nb
```

```
SOLVE
FINISH

/POST26
NSOL,2,nm,U,Z
/axlab,y,Displacement (um)
/AXLAB,x,Pressure (Pa)
PLVAR,2
FINISH
```

11.3 Corrugation implementation

11.3.1 With adaptive reflective region: Modal Analysis

The first eigen frequency is written in an output text file.(output.dat) Modular parameters

- Length: L
- Thickness: t
- Prestress of the SiN: stress
- Prestress of the reflective region material: stress2
- Thickness of the reflective region: tg
- Radius of the reflective region:r (Must be strictly smaller than the position of the first corrugation)
- Material used for the reflective region
- Number of corrugation: iter
- Width of the corrugation : c
- Height of the corrugation : h
- Space between two corrugations : c2
- Position of the first corrugation : rc (Must be strictly higher than the radius of the reflective region)

```
FINISH
/CLEAR

/UNITS,uMKS

*SET,anchor,25
*SET,t,50e-3
*SET,tg,30e-3
*SET,l,1e3
*SET,stress,50
*SET,stress2,-100
r=25
rc=29
c=10
h=5
iter=2
c2=5
*DIM,MYARRAY,ARRAY,1,1

/PREP7

MP,EX,1,200e3
MP,NUXY,1,0.25
MP,DENS,1,3300e-18

MP, EX, 2, 75e3
MP, NUXY,2,0.33
MP,DENS,2,2700e-18

K,001,0                ,0               ,0
K,002,L/2              ,0               ,0
K,003,L/2+anchor       ,0               ,0

K,011,0                ,L/2             ,0
K,012,L/2              ,L/2             ,0
```

```
K,013,L/2+anchor,L/2              ,0

K,021,0                  ,L/2+anchor      ,0
K,022,L/2                ,L/2+anchor      ,0
K,023,L/2+anchor,L/2+anchor       ,0

K,101,0                  ,0               ,t
K,102,L/2                ,0               ,t
K,103,L/2+anchor,0                ,t

K,111,0                  ,L/2             ,t
K,112,L/2                ,L/2             ,t
K,113,L/2+anchor,L/2              ,t

K,121,0                  ,L/2+anchor      ,t
K,122,L/2                ,L/2+anchor      ,t
K,123,L/2+anchor,L/2+anchor       ,t

/vup,1,z
/VIEW,1,1,-1,1
/PNUM,KP,1
KPLOT

*DO,k,0,000,100
*DO,j,0,10,10
*DO,i,0,1,1
V,1+i+j+k,2+i+j+k,12+i+j+k,11+i+j+k,101+i+j+k,102+i+j+k,112+i+j+k,111+i+j+kvplot
*ENDDO
*ENDDO
*ENDDO
VPLOT

CYL4,0,0,0,0,rc+(c+c2)*iter,90,tg+t
VSBV,1,5
CYLIND,0,r,0,t,0,90
CYLIND,0,r,0,-tg,0,90
ALLSEL,ALL
VGLUE,5,1

CYLIND,r,rc,0,t,0,90

*DO,iii,1,iter,1
CYLIND,rc+((c+c2)*(iii-1)),rc+((c+c2)*(iii-1))+c2,0,t,0,90
CYLIND,rc+c2+((c+c2)*(iii-1)),rc+c2+c+((c+c2)*(iii-1)),h,t+h,0,90
CYLIND,rc+c2+((c+c2)*(iii-1)),rc+t+c2+((c+c2)*(iii-1)),0,t,0,90
CYLIND,rc+c2+((c+c2)*(iii-1)),rc+t+c2+((c+c2)*(iii-1)),t,h,0,90
CYLIND,rc+c2-t+c+((c+c2)*(iii-1)),rc+c2+c+((c+c2)*(iii-1)),t,h,0,90
CYLIND,rc+c2-t+c+((c+c2)*(iii-1)),rc+c2+c+((c+c2)*(iii-1)),0,t,0,90
*ENDDO

K,5200,0,0,-h-t
K,5201,0,0,t+h
K,5202,l/2,L/2,t+h
K,5203,l/2,L/2,-h-t
```

```
A,5200,5201,5202,5203
VSEL,S,VOLU,,ALL
VSEL,U,VOLU,,2,4
KSEL,S,KP,,5200
LSLK,S,0
ASLL,S,0
VSBA,ALL,ALL
ALLSEL,ALL

NUMMRG,KP,1E-3
/PNUM,VOLU,1
VPLOT

ALLSEL,ALL
ET,1,SOLID185
MOPT,TRANS,1.2
MOPT,SPLIT,2

ESIZE,10
VSEL,S,LOC,X,0,r
VSEL,R,LOC,Y,0,r
VSEL,R,LOC,Z,0,-tg
VSEL,INVE
TYPE,1
SECNUM,1
MAT,1
VMESH,ALL
ALLSEL,ALL

VSEL,S,LOC,X,0,r
VSEL,R,LOC,Y,0,r
VSEL,R,LOC,Z,0,-tg
MAT,2
VMESH,ALL
ALLSEL,ALL

NUMMRG,KP,1e-3
NUMMRG,NODE,1e-3

INISTATE,SET,MAT,1
INISTATE,DEFINE,,,,,stress,stress
ALLSEL,ALL,ALL

INISTATE,SET,MAT,2
INISTATE,DEFINE,,,,,stress2,stress2
ALLSEL,ALL,ALL

ASEL,S,AREA,,7
ASEL,A,AREA,,17
ASEL,A,AREA,,12
NSLA,S,1
D,ALL,ALL,0
ALLSEL,ALL,ALL
```

```
NSEL,S,LOC,X,0,L/2
NSEL,R,LOC,Y,0,0
NSEL,R,LOC,Z,-tg,t+h
D,ALL,UY,0
ALLSEL,ALL,ALL

NSEL,S,LOC,Y,0,L/2
NSEL,R,LOC,X,0,0
NSEL,R,LOC,Z,-tg,t+h
D,ALL,UX,0
ALLSEL,ALL,ALL

FINISH
/SOLU
ANTYPE,STATIC,NEW                    ! Static analysis
PSTRESS,ON
SOLVE
FINISH

/POST1
/DSCALE,ALL,1
/CONTOUR,ALL,128
PLNSOL,U,Z
FINISH

/SOL
ANTYPE,MODAL            ! Modal analysis
MODOPT,LANB,5,1e4
MXPAND,5
PSTRESS,ON
SOLVE
FINISH

/POST1
/DSCALE,ALL,AUTO
/CONTOUR,ALL,128
SET,FIRST
*get,freq1,active,,set,freq
MYARRAY(1,1)=freq1*1e-3

*CFOPEN,output,dat
*VWRITE,MYARRAY(1,1)
(E20.10)
*CFCLOSE,output,dat
```

11.3.2 With adaptive reflective region: Static Analysis without any pressure applied

The initial displacement without any load is written in an output text file. (output2.dat) Modular parameters

- Length: L
- Thickness: t
- Prestress of the SiN: stress
- Prestress of the reflective region material: stress2
- Thickness of the reflective region: tg
- Radius of the reflective region:r (Must be strictly smaller than the position of the first corrugation)
- Material used for the reflective region
- Applied pressure: press
- Number of corrugation: iter
- Width of the corrugation : c
- Height of the corrugation : h
- Space between two corrugations : c2
- Position of the first corrugation : rc (Must be strictly higher than the radius of the reflective region)

```
FINISH
/CLEAR

/UNITS,uMKS

*SET,anchor,25
*SET,t,50e-3
*SET,tg,30e-3
*SET,l,1e3
*SET,stress,50
*SET,stress2,-100
r=25
rc=29
c=10
h=5
iter=2
c2=5
nb=200
*DIM,MYARRAY,ARRAY,1,1

/PREP7

MP,EX,1,200e3
MP,NUXY,1,0.25
MP,DENS,1,3300e-18

MP, EX, 2, 75e3
MP, NUXY,2,0.33
MP,DENS,2,2700e-18

K,001,0                    ,0                 ,0
K,002,L/2                  ,0                 ,0
K,003,L/2+anchor           ,0                 ,0

K,011,0                    ,L/2               ,0
```

```
K,012,L/2                 ,L/2              ,0
K,013,L/2+anchor          ,L/2              ,0

K,021,0                   ,L/2+anchor       ,0
K,022,L/2                 ,L/2+anchor       ,0
K,023,L/2+anchor          ,L/2+anchor       ,0

K,101,0                   ,0                ,t
K,102,L/2                 ,0                ,t
K,103,L/2+anchor          ,0                ,t

K,111,0                   ,L/2              ,t
K,112,L/2                 ,L/2              ,t
K,113,L/2+anchor          ,L/2              ,t

K,121,0                   ,L/2+anchor       ,t
K,122,L/2                 ,L/2+anchor       ,t
K,123,L/2+anchor          ,L/2+anchor       ,t

/vup,1,z
/VIEW,1,1,-1,1
/PNUM,KP,1
KPLOT

*DO,k,0,000,100
*DO,j,0,10,10
*DO,i,0,1,1
V,1+i+j+k,2+i+j+k,12+i+j+k,11+i+j+k,101+i+j+k,102+i+j+k,112+i+j+k,111+i+j+kvplot
*ENDDO
*ENDDO
*ENDDO
VPLOT

CYL4,0,0,0,0,rc+(c+c2)*iter,90,tg+t
VSBV,1,5
CYLIND,0,r,0,t,0,90
CYLIND,0,r,0,-tg,0,90
ALLSEL,ALL
VGLUE,5,1

CYLIND,r,rc,0,t,0,90

*DO,iii,1,iter,1

CYLIND,rc+((c+c2)*(iii-1)),rc+((c+c2)*(iii-1))+c2,0,t,0,90
CYLIND,rc+c2+((c+c2)*(iii-1)),rc+c2+c+((c+c2)*(iii-1)),h,t+h,0,90
CYLIND,rc+c2+((c+c2)*(iii-1)),rc+t+c2+((c+c2)*(iii-1)),0,t,0,90
CYLIND,rc+c2+((c+c2)*(iii-1)),rc+t+c2+((c+c2)*(iii-1)),t,h,0,90
CYLIND,rc+c2-t+c+((c+c2)*(iii-1)),rc+c2+c+((c+c2)*(iii-1)),t,h,0,90
CYLIND,rc+c2-t+c+((c+c2)*(iii-1)),rc+c2+c+((c+c2)*(iii-1)),0,t,0,90

*ENDDO

K,5200,0,0,-h-t
```

```
K,5201,0,0,t+h
K,5202,l/2,L/2,t+h
K,5203,l/2,L/2,-h-t

A,5200,5201,5202,5203
VSEL,S,VOLU,,ALL
VSEL,U,VOLU,,2,4
KSEL,S,KP,,5200
LSLK,S,0
ASLL,S,0
VSBA,ALL,ALL
ALLSEL,ALL

NUMMRG,KP,1E-3
/PNUM,VOLU,1
VPLOT

ALLSEL,ALL
ET,1,SOLID185
MOPT,TRANS,1.2
MOPT,SPLIT,2

ESIZE,10
VSEL,S,LOC,X,0,r
VSEL,R,LOC,Y,0,r
VSEL,R,LOC,Z,0,-tg
VSEL,INVE
TYPE,1
SECNUM,1
MAT,1
VMESH,ALL
ALLSEL,ALL

VSEL,S,LOC,X,0,r
VSEL,R,LOC,Y,0,r
VSEL,R,LOC,Z,0,-tg
MAT,2
!TYPE,2
!SECNUM,2
VMESH,ALL
ALLSEL,ALL

NUMMRG,KP,1e-3
NUMMRG,NODE,1e-3

INISTATE,SET,MAT,1
INISTATE,DEFINE,,,,,stress,stress
ALLSEL,ALL,ALL

INISTATE,SET,MAT,2
INISTATE,DEFINE,,,,,stress2,stress2
ALLSEL,ALL,ALL

ASEL,S,AREA,,7
```

```
ASEL,A,AREA,,17
ASEL,A,AREA,,12
NSLA,S,1
D,ALL,ALL,0
ALLSEL,ALL,ALL

NSEL,S,LOC,X,0,L/2
NSEL,R,LOC,Y,0,0
NSEL,R,LOC,Z,-tg,t+h
D,ALL,UY,0
ALLSEL,ALL,ALL

NSEL,S,LOC,Y,0,L/2
NSEL,R,LOC,X,0,0
NSEL,R,LOC,Z,-tg,t+h
D,ALL,UX,0
ALLSEL,ALL,ALL

FINISH
/SOL
ANTYPE,STATIC,NEW              ! Static analysis
NLGEOM,ON   !non-linearities
NCNV,,1E20
!KBC,0
TIME,press
*SET,nm,node(0,0,0)
MONITOR,1,nm,uz
OUTRES,all,all !write the result at every step
NEQIT,800
!NSUBST,nb,8000,nb
SOLVE
FINISH

/POST26
NSOL,2,nm,U,Z
/axlab,y,Displacement (um)
/AXLAB,x,Pressure (Pa)
PLVAR,2
FINISH

/POST1
/DSCALE,ALL,1.0
/CONTOUR,ALL,128
SET,LAST
PLNSOL,UZ
NSEL,S,LOC,X,0,0
NSEL,R,LOC,Y,0,0
NSEL,R,LOC,Z,0,0
*get,nmi,NODE,,NUM,MAX
*get,uznm,NODE,nmi,UZ
MYARRAY(1,1)=uznm


*CFOPEN,output2,dat
```

```
*VWRITE,MYARRAY(1,1)
(E20.10)
*CFCLOSE,output2,dat
```

11.3.3 With adaptive reflective region: Static Analysis to determine only the limit of detection

The displacement at 0.02Pa is written in an output text file. (output_stress.dat) Modular parameters

- Length: L
- Thickness: t
- Prestress of the SiN: stress
- Prestress of the reflective region material: stress2
- Thickness of the reflective region: tg
- Radius of the reflective region:r (Must be strictly smaller than the position of the first corrugation)
- Material used for the reflective region
- Fixed applied pressure: pressf
- Number of corrugation: iter
- Width of the corrugation : c
- Height of the corrugation : h
- Space between two corrugations : c2
- Position of the first corrugation : rc (Must be strictly higher than the radius of the reflective region)

```
FINISH
/CLEAR

/UNITS,uMKS

*SET,anchor,25
*SET,t,50e-3
*SET,tg,30e-3
*SET,l,1e3
*SET,l,1e3
*SET,stress,50
*SET,pressf,0.02E-6
*SET,stress2,-100
r=25
rc=29
c=10
h=5
iter=2
c2=5
nb=200
*DIM,MYARRAY,ARRAY,1,1

/PREP7

MP,EX,1,200e3
MP,NUXY,1,0.25
MP,DENS,1,3300e-18

MP, EX, 2, 75e3
MP, NUXY,2,0.33
MP,DENS,2,2700e-18


K,001,0                    ,0                    ,0
```

```
K,002,L/2               ,0              ,0
K,003,L/2+anchor        ,0              ,0

K,011,0                 ,L/2            ,0
K,012,L/2               ,L/2            ,0
K,013,L/2+anchor        ,L/2            ,0

K,021,0                 ,L/2+anchor     ,0
K,022,L/2               ,L/2+anchor     ,0
K,023,L/2+anchor        ,L/2+anchor     ,0

K,101,0                 ,0              ,t
K,102,L/2               ,0              ,t
K,103,L/2+anchor        ,0              ,t

K,111,0                 ,L/2            ,t
K,112,L/2               ,L/2            ,t
K,113,L/2+anchor        ,L/2            ,t

K,121,0                 ,L/2+anchor     ,t
K,122,L/2               ,L/2+anchor     ,t
K,123,L/2+anchor        ,L/2+anchor     ,t

/vup,1,z
/VIEW,1,1,-1,1
/PNUM,KP,1
KPLOT

*DO,k,0,000,100
*DO,j,0,10,10
*DO,i,0,1,1
V,1+i+j+k,2+i+j+k,12+i+j+k,11+i+j+k,101+i+j+k,102+i+j+k,112+i+j+k,111+i+j+kvplot
*ENDDO
*ENDDO
*ENDDO
VPLOT

CYL4,0,0,0,0,rc+(c+c2)*iter,90,tg+t
VSBV,1,5
CYLIND,0,r,0,t,0,90
CYLIND,0,r,0,-tg,0,90
ALLSEL,ALL
VGLUE,5,1

CYLIND,r,rc,0,t,0,90

*DO,iii,1,iter,1

CYLIND,rc+((c+c2)*(iii-1)),rc+((c+c2)*(iii-1))+c2,0,t,0,90
CYLIND,rc+c2+((c+c2)*(iii-1)),rc+c2+c+((c+c2)*(iii-1)),h,t+h,0,90
CYLIND,rc+c2+((c+c2)*(iii-1)),rc+t+c2+((c+c2)*(iii-1)),0,t,0,90
CYLIND,rc+c2+((c+c2)*(iii-1)),rc+t+c2+((c+c2)*(iii-1)),t,h,0,90
CYLIND,rc+c2-t+c+((c+c2)*(iii-1)),rc+c2+c+((c+c2)*(iii-1)),t,h,0,90
CYLIND,rc+c2-t+c+((c+c2)*(iii-1)),rc+c2+c+((c+c2)*(iii-1)),0,t,0,90
```

```
*ENDDO

K,5200,0,0,-h-t
K,5201,0,0,t+h
K,5202,l/2,L/2,t+h
K,5203,l/2,L/2,-h-t

A,5200,5201,5202,5203
VSEL,S,VOLU,,ALL
VSEL,U,VOLU,,2,4
KSEL,S,KP,,5200
LSLK,S,0
ASLL,S,0
VSBA,ALL,ALL
ALLSEL,ALL

NUMMRG,KP,1E-3
/PNUM,VOLU,1
VPLOT

ALLSEL,ALL
ET,1,SOLID185
MOPT,TRANS,1.2
MOPT,SPLIT,2

ESIZE,10
VSEL,S,LOC,X,0,r
VSEL,R,LOC,Y,0,r
VSEL,R,LOC,Z,0,-tg
VSEL,INVE
TYPE,1
SECNUM,1
MAT,1
VMESH,ALL
ALLSEL,ALL

VSEL,S,LOC,X,0,r
VSEL,R,LOC,Y,0,r
VSEL,R,LOC,Z,0,-tg
MAT,2
VMESH,ALL
ALLSEL,ALL

NUMMRG,KP,1e-3
NUMMRG,NODE,1e-3

INISTATE,SET,MAT,1
INISTATE,DEFINE,,,,,stress,stress
ALLSEL,ALL,ALL

INISTATE,SET,MAT,2
INISTATE,DEFINE,,,,,stress2,stress2
ALLSEL,ALL,ALL
```

```
ASEL,S,AREA,,7
ASEL,A,AREA,,17
ASEL,A,AREA,,12
NSLA,S,1
D,ALL,ALL,0
ALLSEL,ALL,ALL

NSEL,S,LOC,X,0,L/2
NSEL,R,LOC,Y,0,L/2
NSEL,R,LOC,Z,t,t
SF,ALL,PRES,pressf

NSEL,S,LOC,X,0,L/2
NSEL,R,LOC,Y,0,L/2
NSEL,R,LOC,Z,h+t,h+t
SF,ALL,PRES,pressf

NSEL,S,LOC,X,0,L/2
NSEL,R,LOC,Y,0,0
NSEL,R,LOC,Z,-tg,t+h
D,ALL,UY,0
ALLSEL,ALL,ALL

NSEL,S,LOC,Y,0,L/2
NSEL,R,LOC,X,0,0

NSEL,R,LOC,Z,-tg,t+h
D,ALL,UX,0
ALLSEL,ALL,ALL

FINISH
/SOL
ANTYPE,STATIC,NEW
NLGEOM,ON
NCNV,,1E20
!KBC,0
TIME,press
*SET,nm,node(0,0,0)
MONITOR,1,nm,uz
OUTRES,all,all
NEQIT,800
!NSUBST,nb,8000,nb
SOLVE
FINISH

/POST26
NSOL,2,nm,U,Z
/axlab,y,Displacement (um)
/AXLAB,x,Pressure (Pa)
PLVAR,2
FINISH

/POST1
```

```
/DSCALE,ALL,1.0
/CONTOUR,ALL,128
SET,LAST
PLNSOL,UZ
NSEL,S,LOC,X,0,0
NSEL,R,LOC,Y,0,0
NSEL,R,LOC,Z,0,0
*get,nmi,NODE,,NUM,MAX
*get,uznm,NODE,nmi,UZ
MYARRAY(1,1)=uznm

*CFOPEN,output_stress,dat
*VWRITE,MYARRAY(1,1)
(E20.10)
*CFCLOSE,output_stress,dat
```

11.3.4 With adaptive reflective region, Static Analysis

A text file with the displacement for each pressure step is written with a monitor option. (file.mnrt)
Modular parameters

- Length: L
- Thickness: t
- Prestress of the SiN: stress
- Prestress of the reflective region material: stress2
- Thickness of the reflective region: tg
- Radius of the reflective region:r (Must be strictly smaller than the position of the first corrugation)
- Material used for the reflective region
- Applied pressure: press
- Number of pressure step: nb
- Number of corrugation: iter
- Width of the corrugation : c
- Height of the corrugation : h
- Space between two corrugations : c2
- Position of the first corrugation : rc (Must be strictly higher than the radius of the reflective region)

```
FINISH
/CLEAR

/UNITS,uMKS

*SET,anchor,25
*SET,t,50e-3
*SET,tg,30e-3
*SET,l,1e3
*SET,l,1e3
*SET,stress,50
*SET,press,20E-6
*SET,stress2,-100
r=25
rc=29
c=10
h=5
iter=2
c2=5
nb=200
*DIM,MYARRAY,ARRAY,1,1

/PREP7

MP,EX,1,200e3
MP,NUXY,1,0.25
MP,DENS,1,3300e-18

MP, EX, 2, 75e3
MP, NUXY,2,0.33
MP,DENS,2,2700e-18

K,001,0                     ,0                  ,0
K,002,L/2                   ,0                  ,0
```

```
K,003,L/2+anchor       ,0               ,0

K,011,0                ,L/2             ,0
K,012,L/2              ,L/2             ,0
K,013,L/2+anchor       ,L/2             ,0

K,021,0                ,L/2+anchor      ,0
K,022,L/2              ,L/2+anchor      ,0
K,023,L/2+anchor       ,L/2+anchor      ,0

K,101,0                ,0               ,t
K,102,L/2              ,0               ,t
K,103,L/2+anchor       ,0               ,t

K,111,0                ,L/2             ,t
K,112,L/2              ,L/2             ,t
K,113,L/2+anchor       ,L/2             ,t

K,121,0                ,L/2+anchor      ,t
K,122,L/2              ,L/2+anchor      ,t
K,123,L/2+anchor       ,L/2+anchor      ,t

/vup,1,z
/VIEW,1,1,-1,1
/PNUM,KP,1
KPLOT

*DO,k,0,000,100
*DO,j,0,10,10
*DO,i,0,1,1
V,1+i+j+k,2+i+j+k,12+i+j+k,11+i+j+k,101+i+j+k,102+i+j+k,112+i+j+k,111+i+j+kvplot
*ENDDO
*ENDDO
*ENDDO
VPLOT

CYL4,0,0,0,0,rc+(c+c2)*iter,90,tg+t
VSBV,1,5
CYLIND,0,r,0,t,0,90
CYLIND,0,r,0,-tg,0,90
ALLSEL,ALL
VGLUE,5,1

CYLIND,r,rc,0,t,0,90

*DO,iii,1,iter,1

CYLIND,rc+((c+c2)*(iii-1)),rc+((c+c2)*(iii-1))+c2,0,t,0,90
CYLIND,rc+c2+((c+c2)*(iii-1)),rc+c2+c+((c+c2)*(iii-1)),h,t+h,0,90
CYLIND,rc+c2+((c+c2)*(iii-1)),rc+t+c2+((c+c2)*(iii-1)),0,t,0,90
CYLIND,rc+c2+((c+c2)*(iii-1)),rc+t+c2+((c+c2)*(iii-1)),t,h,0,90
CYLIND,rc+c2-t+c+((c+c2)*(iii-1)),rc+c2+c+((c+c2)*(iii-1)),t,h,0,90
CYLIND,rc+c2-t+c+((c+c2)*(iii-1)),rc+c2+c+((c+c2)*(iii-1)),0,t,0,90
```

```
*ENDDO

K,5200,0,0,-h-t
K,5201,0,0,t+h
K,5202,l/2,L/2,t+h
K,5203,l/2,L/2,-h-t

A,5200,5201,5202,5203
VSEL,S,VOLU,,ALL
VSEL,U,VOLU,,2,4
KSEL,S,KP,,5200
LSLK,S,0
ASLL,S,0
VSBA,ALL,ALL
ALLSEL,ALL

NUMMRG,KP,1E-3
/PNUM,VOLU,1
VPLOT

ALLSEL,ALL
ET,1,SOLID185
MOPT,TRANS,1.2
MOPT,SPLIT,2

ESIZE,10
VSEL,S,LOC,X,0,r
VSEL,R,LOC,Y,0,r
VSEL,R,LOC,Z,0,-tg
VSEL,INVE
TYPE,1
SECNUM,1
MAT,1
VMESH,ALL
ALLSEL,ALL

VSEL,S,LOC,X,0,r
VSEL,R,LOC,Y,0,r
VSEL,R,LOC,Z,0,-tg
MAT,2
VMESH,ALL
ALLSEL,ALL

NUMMRG,KP,1e-3
NUMMRG,NODE,1e-3

INISTATE,SET,MAT,1
INISTATE,DEFINE,,,,,stress,stress
ALLSEL,ALL,ALL

INISTATE,SET,MAT,2
INISTATE,DEFINE,,,,,stress2,stress2
ALLSEL,ALL,ALL
```

```
ASEL,S,AREA,,7
ASEL,A,AREA,,17
ASEL,A,AREA,,12
NSLA,S,1
D,ALL,ALL,0
ALLSEL,ALL,ALL

NSEL,S,LOC,X,0,L/2
NSEL,R,LOC,Y,0,L/2
NSEL,R,LOC,Z,t,t
SF,ALL,PRES,press

NSEL,S,LOC,X,0,L/2
NSEL,R,LOC,Y,0,L/2
NSEL,R,LOC,Z,h+t,h+t
SF,ALL,PRES,press

NSEL,S,LOC,X,0,L/2
NSEL,R,LOC,Y,0,0
NSEL,R,LOC,Z,-tg,t+h
D,ALL,UY,0
ALLSEL,ALL,ALL

NSEL,S,LOC,Y,0,L/2
NSEL,R,LOC,X,0,0

NSEL,R,LOC,Z,-tg,t+h
D,ALL,UX,0
ALLSEL,ALL,ALL

FINISH
/SOL
ANTYPE,STATIC,NEW                ! Static analysis
NLGEOM,ON
NCNV,,1E20
KBC,0
TIME,press
*SET,nm,node(0,0,0)
MONITOR,1,nm,uz
OUTRES,all,all
NEQIT,800
NSUBST,nb,8000,nb
SOLVE
FINISH

/POST26
NSOL,2,nm,U,Z
/axlab,y,Displacement (um)
/AXLAB,x,Pressure (Pa)
PLVAR,2
FINISH

/POST1
/DSCALE,ALL,1.0
```

```
/CONTOUR,ALL,128
SET,LAST
PLNSOL,UZ
```

11.3.5 Matlab function that runs the Ansys codes and Matlab optimization code

A matlab function that runs 4 Ansys codes and that returns 3 outputs : The first eigen frequency, the displacement at the fixed applied pressure (at 0.02 Pa to have the limit of detection) and the value of the pressure at which the displacement is not linear anymore (limit of linearity).
The four codes presented in the section above have to be in the same folder than this matlab function. The first code that return the first eigen frequency has to be named "Modal.txt", the second that return the initial displacement without any loads has to be named "Stress_0.txt", the third that returns the displacement at 0.02 Pa "Stress.txt" and the last "Stress_linear.txt". In all the four text file the parameters definitions have to be substituted by command "$/input, parameters, txt$". Indeed, the parameters can now be set by the matlab code and written in the text file named parameters.txt.

```
function [Output] = FE()

anchor=25;
t=50e-3;
tg=30e-3;
l=1e3;
stress=50;
pressf=0.02E-6;
press=200E-6;
stress2=-100;
r=25;
rc=29;
c=10;
h=5;
iter=2;
c2=5;

fid=fopen('parameters.txt','w');
fprintf(fid,'/NOPR \n');
fprintf(fid,'*SET,anchor,%g \n',anchor);
fprintf(fid,'*SET,t,%g \n',t);
fprintf(fid,'*SET,tg,%g \n',tg);
fprintf(fid,'*SET,l,%g \n',l);
fprintf(fid,'*SET,stress,%g \n',stress);
fprintf(fid,'*SET,stress2,%g \n',stress2);
fprintf(fid,'*SET,press,%g \n',press);
fprintf(fid,'*SET,pressf,%g \n',pressf);
fprintf(fid,'*SET,r,%g \n',r);
fprintf(fid,'*SET,rc,%g \n',rc);
fprintf(fid,'*SET,c,%g \n',c);
fprintf(fid,'*SET,h,%g \n',h);
fprintf(fid,'*SET,iter,%g \n',iter);
fprintf(fid,'*SET,c2,%g \n',c2);
fprintf(fid,'/GO \n');
fclose(fid);

! SET KMP_STACKSIZE=2048k & "C:\Program Files\Ansys Inc\V172\ANSYS\bin
\winx64\ansys172" -m 8192 -db 4096 -b -i Modal.txt -o OPModal.txt

! SET KMP_STACKSIZE=2048k & "C:\Program Files\Ansys Inc\V172\ANSYS\bin
\winx64\ansys172" -m 8192 -db 4096 -b -i Stress_0.txt -o OPStress_0.txt
```

```
! SET KMP_STACKSIZE=2048k & "C:\Program Files\Ansys Inc\V172\ANSYS\bin
\winx64\ansys172" -m 8192 -db 4096 -b -i Stress.txt -o OPStress.txt

! SET KMP_STACKSIZE=2048k & "C:\Program Files\Ansys Inc\V172\ANSYS\bin
\winx64\ansys172" -m 8192 -db 4096 -b -i Stress_linear.txt -o OPStress.txt


data_freq=load('output.dat')
data1=load('output2.dat');
data2=load('output_stress.dat');
data_linear=dlmread('file.mntr',' ',10,0);
data_disp_min=(data1-data2)*10^3;


p=polyfit(data_linear(1:4,7),data_linear(1:4,8),1);
x=linspace(0,data_linear(end,7),length(data_linear(:,8)));
y=p(1)*x+p(2);

s=0;
for i=1:length(y)
diff(i)=abs(((data_linear(i,8)-y(i))*100)./y(i));

if diff(i)*100>=2 && s==0
    s=1;
    ML=data_linear(i,7)
end
end


Output(1)=data_freq;
Output(2)=data_disp_min;
Output(3)=ML*10^6;

end
```

This function can be just run in a matlab script with all the parameters define. But it can also be use to produce a map of the results for all the parameters or some of them. To do so, the parameters concerned have to be put in input of the function, example : FE(l,rc,iter), and remove from the function above, then the following code as an example can be run :

```
clear all
close all
clc

l=[700,750,900,950,1000,1500,2500,3000];
rc=[25:5:60];
iter=[2:1:15];

for i=1:1:length(l)
    for k=1:1:length(rc)
        for j=1:1:length(iter)
```

```
                Output=FE(l(i),rc(j),iter(k));
                Data(i,j,k,1)=Output(1);
                Data(i,j,k,2)=Output(2);
                Data(i,j,k,3)=Output(3);
            end
        end
    end

    save('Data.mat','Data')
```

This loop create a 4-D matrix that contains the three output parameters values that can be post processed as needed.
Moreover the Matlab function FE can also be used to optimize the results depending on the parameters of interest as explained in the section 9. But in this function the penalty condition has to be added in order that if the frequency in under a specified value the code gives it a very low value that eliminates this candidates to the optimization the following piece of coding has to be added in the function just before the Output definition :

```
cutoff_freq=100;
if data_freq<cutoff_freq
        data_freq=0.1;
end
```

But it is important to notice that for this penalty function to work the initial point have to has a natural frequency higher that the chosen cutoff frequency. All the matlab function presented in the figure 44 are given below for the optimization with the parameters : Length, number of corrugation and the position of the first corrugation as an example.

- The script Start.m that launch the optimization by given the function to optimize and the initial parameters to the optimization function.

  ```
  clear all;
  close all;
  clc

  l=1000;
  iter=2;
  rc=50;

  param=[l,rc,iter];

  optimization(@OBJ,3)
  ```

- The function OBJ, this is the function to optimize. In this case the function 1/f*d is minimized by the function optimization. f is the first eigen frequency and d the limit of detection given by the Ansys simulation.

  ```
  function Tooptimize = OBJ(param)

  Output=FE(param(1),param(2),param(3));
  f=Output(1);
  d=Output(2);
  Tooptimize=1/(d*f);
  end
  ```

- The function optimization that minimize with the function "particleswarm" the function OBJ presented above, by attempting to find a vector x that achieves a local minimum of the function OBJ, nvars is the dimension (number of design variables) of OBJ. minX and maxX defines a set of lower and upper bounds on the design variables, param, so that a solution is found in the range $minX < param < maxX$.

```
function [x,fval,exitflag,output,lambda,grad,hessian]=optimization(ObjFct,par
warning off;
if ~exist('parm','var')

end
if ~exist('tolfun','var')
    tolfun=1e-7;
end
if ~exist('tolx','var')
    tolx=1e-4;
end
if ~exist('diff','var')
    diff=0.05;
end
if ~exist('maxit','var')
    maxit=20;
end
minX=zeros(size(param));

minX=[750 25.01 2];
maxX=[3000 60 15];
fileID = fopen('Visu.txt','w');
fprintf(fileID,' Param-1                          Err max
Err mean\r\n\r\n');
fclose(fileID);

[x,fval,exitflag,output] = particleswarm(ObjFct,nvar,minX,maxX);
```

11.4 Matlab analytic function determination to optimize

As explained in the section 9, an analytical function of the first eigen frequency and of the displacement at 0.02 Pa is computed by the following code. At the end the values of the parameters can be implemented and the values of the frequency and of the displacement associated are given.

```
clear all;
close all;

Commun geometry

L=1000; %[um]
e=0.05; %[um]
r=25; %[um]
n= 1; %
c=3; %
h=1.5; %
```

```
p=50; %
s=450; %

f_0=268.4;
d_0=0.0689;

Influence of the length
L= [3500            3000      2500      2000      1500      1000      750];
fL= [78.8           92        110.3     137.4     182.3     268.4     347.8]./f_0;
dL= [0.8            0.6       0.4       0.2565    0.1471    0.0689    0.0417]./d_0;

figure (1)
plot(L,fL)
hold on
plot(L,dL)
hold off
xlabel('Length [\mum]');
ylabel('f/f_0, d/d_0');
legend ('Frequency','Displacement')

figure(11)
plot(L,fL.*dL)
xlabel('Length [\mum]');
ylabel('f*d [kHz*nm]');

Influence of the thickness
e=[0.5    0.3       0.2       0.1       0.05      0.03      0.02];
fe=[268.4           268.4     268.4     268.4     268.4     268.4     268.4]./f_0;
de=[0.00655         0.01102   0.01666   0.0337    0.0689    0.1166    0.1748]./d_0;

figure(2)
plot(e,fe)
hold on
plot(e,de)
hold off
xlabel('Thickness [\mum]')
ylabel('f/f_0, d/d_0')
legend ('Frequency','Displacement')

figure(22)
plot(e,fe.*de)
xlabel('Thickness [\mum]')
ylabel('f*d [kHz*nm]')

Influence of the nb of corrugations

n=[0      1         2         3         4           12 15 20];
fn=[276   268.4     266       263       259       187 154.5 117]./f_0;
dn=[0.061           0.0689    0.0725    0.0762    0.0791 1.45E-01 1.88E-01 2.95E-01]./d_0;

figure(3)
plot(n,fn)
hold on
plot(n,dn)
```

```
hold off
xlabel('Number of corrugation [-]')
ylabel('f/f_0, d/d_0')
legend ('Frequency','Displacement')

figure(33)
plot(n,fn.*dn)
xlabel('Number of corrugation [-]')
ylabel('f*d [kHz*nm]')
Influence of the width of the corrugation

c=[     3       4       5       6       7       10      12];
fc=[268.4       268     267.5   267     266     264     263]./f_0;
dc=[0.065       0.0656  0.066   0.0663  0.0665  0.0673  0.068]./d_0;

figure(4)
plot(c,fc)
hold on
plot(c,dc)
hold off
xlabel('Width of the corrugations [\mum]')
ylabel('f/f_0, d/d_0')
legend ('Frequency','Displacement')
Influence of the height of the corrugation
h=[ 1   1.5     2       2.5     3.5     ];
fh=[  269.7     268.4   268     267.69  266.88  ]./f_0;
dh=[  0.06372   0.06542 0.06691 0.06863 0.07344 ]./d_0;
figure(5)
plot(h,fh)
hold on
plot(h,dh)
hold off
xlabel('Height of the corrugations [\mum]')
ylabel('f/f_0, d/d_0')
legend ('Frequency','Displacement')
Influence of the position of the corrugation

p=[25   50      100     200     300     400];
fp=[273.8       268.4   220     167     141     126]./f_0;
dp=[0.0625      0.06542 0.07335 0.09    0.1034  0.11379]./d_0;

figure(6)
plot(p,fp)
hold on
plot(p,dp)
hold off
xlabel('Position of the first corrugation [\mum]')
ylabel('f/f_0, d/d_0')
legend ('Frequency','Displacement')
figure(66)
plot(p,fp.*dp)
xlabel('Position of the first corrugation [\mum]')
ylabel('f*d [kHz*nm]')
Influence of the pre stress
```

```
s=[50    150      450      900];
fs=[103  162.5    268.4    369]./f_0;
ds=[5.03E-01     0.1853   0.065    0.0336]./d_0;

figure(7)
plot(s,fs)
hold on
plot(s,ds)
hold off
xlabel('Prestress [MPa]')
ylabel('f/f_0, d/d_0')
legend ('Frequency','Displacement')

figure(77)
plot(s,fs.*ds)
xlabel('Prestress [MPa]')
ylabel('f*d [kHz*nm]')
%%
pdL=polyfit(log(L),log(dL),1);
pdle=polyfit(log(e),log(de),1);
pdn=polyfit(n,dn,2);
pdc=polyfit((c),(dc),1);
pdh=polyfit((h),(dh),1);
pdp=polyfit(p,dp,1);
pdls=polyfit(log(s),log(ds),1);

pL=polyfit(log(L),log(fL),1);
pn=polyfit(n,fn,1);
pc=polyfit(c,fc,1);
ph=polyfit(log(h),log(fh),1);
pp=polyfit(p,fp,2);
ps=polyfit(s,fs,2);

save('constante.mat','pdL','pdle','pdn','pdc','pdh','pdp','pdls','pL','pn','pc',

L=730; % Enter the data here
e=0.05;
n=9;
c=6.1;
h=7.9;
s=50;
p=29;

param=[L,e,n,c,h,s,p];

f_L=exp(pL(2))*L^(pL(1));
f_e=1;
f_n=pn(1)*n+pn(2);
f_c=pc(1)*c+pc(2);
f_h=exp(ph(2))*h^(ph(1));
f_p=pp(1)*p^2+pp(2)*p+pp(3);
f_s=ps(1)*s^2+ps(2)*s+ps(3);
```

```
d_L=exp(pdL(2))*L.^(pdL(1));
d_e=exp(pdle(2))*e.^(pdle(1));
d_n=pdn(1)*n.^2+pdn(2)*n+pdn(3);
d_c=pdc(1)*c+(pdc(2));
d_h=pdh(1)*h+pdh(2);
d_p=pdp(1)*p+pdp(2);
d_s=exp(pdls(2))*s.^(pdls(1));


f=f_0*f_L*f_e*f_n*f_c*f_h*f_p*f_s
d=d_0*d_L*d_e*d_n*d_c*d_h*d_p*d_s
```

Now following the same reflection of optimization the analytical function 1/(f*d) can be minimized by the function optimization presented in the section above. This time the optimization function is fmincon, it allows to minimize this function :

```
function Optm = fonction(param)
load('constante.mat')
f_0=268.4;
d_0=0.0689;

f_L=exp(pL(2))*param(1)^(pL(1));
f_e=1;
f_n=pn(1)*param(3)+pn(2);
f_c=pc(1)*param(4)+pc(2);
f_h=exp(ph(2))*param(5)^(ph(1));
f_p=pp(1)*param(7)^2+pp(2)*param(7)+pp(3);
f_s=ps(1)*param(6)^2+ps(2)*param(6)+ps(3);

d_L=exp(pdL(2))*param(1)^(pdL(1));
d_e=exp(pdle(2))*param(2)^(pdle(1));
d_n=pdn(1)*param(3)^2+pdn(2)*param(3)+pdn(3);
d_c=pdc(1)*param(4)+(pdc(2));
d_h=pdh(1)*param(5)+pdh(2);
d_p=pdp(1)*param(7)+pdp(2);
d_s=exp(pdls(2))*param(6)^(pdls(1));


f=f_0*f_L*f_e*f_n*f_c*f_h*f_p*f_s;
d=d_0*d_L*d_e*d_n*d_c*d_h*d_p*d_s;

Optm=1/((f)*(d));

end
```

With the parameters boundaries minX and maxX.

```
function [x,fval,exitflag,output,lambda,grad,hessian]=optim2(ObjFct,param,tolfun
warning off;
if ~exist('parm','var')

end
if ~exist('tolfun','var')
    tolfun=1e-7;
```

```
end
if ~exist('tolx','var')
    tolx=1e-4;
end
if ~exist('diff','var')
    diff=0.05;
end
if ~exist('maxit','var')
    maxit=20;
end
minX=zeros(size(param));
A = [0 0  ;0 0 ];
b = [0 0];
beq = [ 0 0];
minX=[950 25.1 ];
maxX=[1100 60.1 ];
fileID = fopen('Visu.txt','w');
fprintf(fileID,' Param-1                     Err max     Err mean\r\n\r\n');
fclose(fileID);
%Options = optimset('Jacobian','off','LargeScale','on','levenberg-marquardt','on
%Options = optimset('Jacobian','off','LargeScale','on','Algorithm','Levenberg-Ma
nonlcon=@circlecon;
[x,fval,exitflag,output,lambda,grad,hessian]=fmincon(ObjFct,param,A,b,A,beq,minX
```

The following function add the constrain to the optimization function that the frequency has to stay above 100 khZ.

```
function [c,ceq] = circlecon(param)
Output=Fonction(param)
f=Output(1);
d=Output(2);
cutoff_freq=100;
c=-(f-cutoff_freq);
ceq = [];
```

Once again all those function has to be in the same folder and it only need to launch the optimization with the initial parameters.

11.5 Corrugation but with aluminun all along the membrane

11.5.1 Two solid layers : Modal analysis

Modular parameters

- Length: L
- Thickness: t
- Prestress of the SiN: stress
- Prestress of the reflective region material: stress2
- Thickness of the reflective region: tg
- Material used for the reflective region
- Number of corrugation: iter
- Width of the corrugation : c
- Height of the corrugation : h
- Space between two corrugations : c2
- Position of the first corrugation : r

```
FINISH
/CLEAR

/UNITS,uMKS

*SET,anchor,25
*SET,t,50e-3
*SET,tg,30e-3
*SET,l,1e3
*SET,stress,50
*SET,press,20E-6
*SET,stress2,-100
r=29
c=10
h=5
iter=2
c2=5

/PREP7

MP,EX,1,200e3
MP,NUXY,1,0.25
MP,DENS,1,3300e-18

MP, EX, 2, 75e3
MP, NUXY,2,0.33
MP,DENS,2,2700e-18


K,001,0              ,0            ,0
K,002,L/2            ,0            ,0
K,003,L/2+anchor     ,0            ,0

K,011,0              ,L/2          ,0
K,012,L/2            ,L/2          ,0
K,013,L/2+anchor     ,L/2          ,0
```

```
K,021,0                    ,L/2+anchor      ,0
K,022,L/2                  ,L/2+anchor      ,0
K,023,L/2+anchor           ,L/2+anchor      ,0

K,101,0                    ,0               ,t
K,102,L/2                  ,0               ,t
K,103,L/2+anchor           ,0               ,t

K,111,0                    ,L/2             ,t
K,112,L/2                  ,L/2             ,t
K,113,L/2+anchor           ,L/2             ,t

K,121,0                    ,L/2+anchor      ,t
K,122,L/2                  ,L/2+anchor      ,t
K,123,L/2+anchor           ,L/2+anchor      ,t


/vup,1,z
/VIEW,1,1,-1,1
/PNUM,KP,1
KPLOT

*DO,k,0,000,100
*DO,j,0,10,10
*DO,i,0,1,1
V,1+i+j+k,2+i+j+k,12+i+j+k,11+i+j+k,101+i+j+k,102+i+j+k,112+i+j+k,111+i+j+kvplot
*ENDDO
*ENDDO
*ENDDO
VPLOT


CYL4,0,0,0,0,r+(c+c2)*iter,90,tg+t
VSBV,1,5
CYLIND,0,r,0,t,0,90

ALLSEL,ALL

*DO,iii,1,iter,1

CYLIND,r+((c+c2)*(iii-1)),r+((c+c2)*(iii-1))+c2,0,t,0,90
CYLIND,r+c2+((c+c2)*(iii-1)),r+(c+c2)+((c+c2)*(iii-1)),h,t+h,0,90
CYLIND,r+c2+((c+c2)*(iii-1)),r+t+c2+((c+c2)*(iii-1)),0,t,0,90
CYLIND,r+c2+((c+c2)*(iii-1)),r+t+c2+((c+c2)*(iii-1)),t,h,0,90
CYLIND,r+c2-t+c+((c+c2)*(iii-1)),r+c2+c+((c+c2)*(iii-1)),t,h,0,90
CYLIND,r+c2-t+c+((c+c2)*(iii-1)),r+c2+c+((c+c2)*(iii-1)),0,t,0,90

*ENDDO

NUMMRG,KP,1E-3
/PNUM,VOLU,1
VPLOT

K,5200,0,0,-h-t
```

```
K,5201,0,0,t+h
K,5202,l/2,L/2,t+h
K,5203,l/2,L/2,-h-t


A,5200,5201,5202,5203
VSEL,S,VOLU,,ALL
VSEL,U,VOLU,,2,4
KSEL,S,KP,,5200
LSLK,S,0
ASLL,S,0
VSBA,ALL,ALL
ALLSEL,ALL

NUMMRG,KP,1E-3
/PNUM,VOLU,1
VPLOT

ET,1,SOLID185
VATT,1,,1

VSEL,NONE

K,201,0                         ,0                ,0
K,202,L/2                       ,0                ,0
K,203,L/2                       ,L/2              ,0
K,204,0                         ,L/2              ,0

K,205,0                         ,0                ,-tg
K,206,L/2                       ,0                ,-tg
K,207,L/2                       ,L/2              ,-tg
K,208,0                         ,L/2              ,-tg

V,201,202,203,204,205,206,207,208
CYLIND,0,r+(c+c2)*iter,0,-tg,0,90
VSBV,1,5

CYLIND,0,r,0,-tg,0,90


*DO,iii,1,iter,1

CYLIND,r+((c+c2)*(iii-1))+c2,r+((c+c2)*(iii-1))+c2+t+tg,0,-tg,0,90
CYLIND,r+c2+((c+c2)*(iii-1))+t,r+c2+tg+t+((c+c2)*(iii-1)),0,h-tg,0,90
CYLIND,r+c2+t+((c+c2)*(iii-1)),r+c2+c-t+((c+c2)*(iii-1)),h-tg,h,0,90
CYLIND,r+c2+c-t-tg+((c+c2)*(iii-1)),r+c2+c-t+((c+c2)*(iii-1)),0,h-tg,0,90
CYLIND,r+c2+c-t-tg+((c+c2)*(iii-1)),r+c2+c+((c+c2)*(iii-1)),0,-tg,0,90
CYLIND,r+((c+c2)*(iii-1)),r+c2+((c+c2)*(iii-1)),0,-tg,0,90

*ENDDO

NUMMRG,KP,1E-3
/PNUM,VOLU,1
VPLOT
```

```
K,5200,0,0,-h-t
K,5201,0,0,t+h
K,5202,l/2,L/2,t+h
K,5203,l/2,L/2,-h-t


A,5200,5201,5202,5203
VSEL,R,VOLU,,ALL
!VSEL,U,VOLU,,2,4
KSEL,S,KP,,5200
LSLK,S,0
ASLL,S,0
VSBA,ALL,ALL

ET,2,SOLID185
VATT,2,,2
ALLSEL,ALL

NUMMRG,KP,1e-3
ESIZE,10
VMESH,ALL
NUMMRG,NODE,1e-3

INISTATE,SET,MAT,1
INISTATE,DEFINE,,,,,stress,stress
ALLSEL,ALL,ALL

INISTATE,SET,MAT,2
INISTATE,DEFINE,,,,,stress,stress
ALLSEL,ALL,ALL

ASEL,S,AREA,,7
ASEL,A,AREA,,17
ASEL,A,AREA,,12
NSLA,S,1
D,ALL,ALL,0
ALLSEL,ALL,ALL


NSEL,S,LOC,X,0,L/2
NSEL,R,LOC,Y,0,0
NSEL,R,LOC,Z,-tg,t+h
D,ALL,UY,0
ALLSEL,ALL,ALL


NSEL,S,LOC,Y,0,L/2
NSEL,R,LOC,X,0,0
NSEL,R,LOC,Z,-tg,t+h
D,ALL,UX,0
ALLSEL,ALL,ALL

FINISH
```

```
/SOLU
ANTYPE,STATIC,NEW                    ! Static analysis
PSTRESS,ON
SOLVE
FINISH

/POST1
/DSCALE,ALL,1
/CONTOUR,ALL,128
PLNSOL,U,Z
FINISH

/SOL
ANTYPE,MODAL              ! Modal analysis
MODOPT,LANB,5,1e4
MXPAND,5
PSTRESS,ON
SOLVE
FINISH

/POST1
/DSCALE,ALL,AUTO
/CONTOUR,ALL,128
SET,FIRST
```

11.5.2 Two solid layers : Static analysis

Modular parameters

- Length: L
- Thickness: t
- Prestress of the SiN: stress
- Prestress of the reflective region material: stress2
- Thickness of the reflective region: tg
- Applied pressure : press
- Number of pressure step : nb
- Material used for the reflective region
- Number of corrugation: iter
- Width of the corrugation : c
- Height of the corrugation : h
- Space between two corrugations : c2
- Position of the first corrugation : r

```
FINISH
/CLEAR

/UNITS,uMKS

*SET,anchor,25
*SET,t,50e-3
*SET,tg,30e-3
*SET,l,1e3
*SET,stress,50
*SET,press,20E-6
*SET,stress2,-100
r=29
c=10
h=5
iter=2
c2=5
nb=200
/PREP7


MP,EX,1,200e3
MP,NUXY,1,0.25
MP,DENS,1,3300e-18

MP, EX, 2, 75e3
MP, NUXY,2,0.33
MP,DENS,2,2700e-18


K,001,0                   ,0              ,0
K,002,L/2                 ,0              ,0
K,003,L/2+anchor          ,0              ,0

K,011,0                   ,L/2            ,0
K,012,L/2                 ,L/2            ,0
K,013,L/2+anchor          ,L/2            ,0
```

```
K,021,0             ,L/2+anchor       ,0
K,022,L/2           ,L/2+anchor       ,0
K,023,L/2+anchor    ,L/2+anchor       ,0

K,101,0             ,0                ,t
K,102,L/2           ,0                ,t
K,103,L/2+anchor    ,0                ,t

K,111,0             ,L/2              ,t
K,112,L/2           ,L/2              ,t
K,113,L/2+anchor    ,L/2              ,t

K,121,0             ,L/2+anchor       ,t
K,122,L/2           ,L/2+anchor       ,t
K,123,L/2+anchor    ,L/2+anchor       ,t

/vup,1,z
/VIEW,1,1,-1,1
/PNUM,KP,1
KPLOT

*DO,k,0,000,100
*DO,j,0,10,10
*DO,i,0,1,1
V,1+i+j+k,2+i+j+k,12+i+j+k,11+i+j+k,101+i+j+k,102+i+j+k,112+i+j+k,111+i+j+kvplot
*ENDDO
*ENDDO
*ENDDO
VPLOT

CYL4,0,0,0,0,r+(c+c2)*iter,90,tg+t
VSBV,1,5
CYLIND,0,r,0,t,0,90

ALLSEL,ALL

*DO,iii,1,iter,1

CYLIND,r+((c+c2)*(iii-1)),r+((c+c2)*(iii-1))+c2,0,t,0,90
CYLIND,r+c2+((c+c2)*(iii-1)),r+(c+c2)+((c+c2)*(iii-1)),h,t+h,0,90
CYLIND,r+c2+((c+c2)*(iii-1)),r+t+c2+((c+c2)*(iii-1)),0,t,0,90
CYLIND,r+c2+((c+c2)*(iii-1)),r+t+c2+((c+c2)*(iii-1)),t,h,0,90
CYLIND,r+c2-t+c+((c+c2)*(iii-1)),r+c2+c+((c+c2)*(iii-1)),t,h,0,90
CYLIND,r+c2-t+c+((c+c2)*(iii-1)),r+c2+c+((c+c2)*(iii-1)),0,t,0,90

*ENDDO

NUMMRG,KP,1E-3
/PNUM,VOLU,1
VPLOT

K,5200,0,0,-h-t
K,5201,0,0,t+h
```

```
K,5202,l/2,L/2,t+h
K,5203,l/2,L/2,-h-t


A,5200,5201,5202,5203
VSEL,S,VOLU,,ALL
VSEL,U,VOLU,,2,4
KSEL,S,KP,,5200
LSLK,S,0
ASLL,S,0
VSBA,ALL,ALL
ALLSEL,ALL

NUMMRG,KP,1E-3
/PNUM,VOLU,1
VPLOT

ET,1,SOLID185
VATT,1,,1

VSEL,NONE

K,201,0              ,0          ,0
K,202,L/2            ,0          ,0
K,203,L/2            ,L/2        ,0
K,204,0              ,L/2        ,0

K,205,0              ,0          ,-tg
K,206,L/2            ,0          ,-tg
K,207,L/2            ,L/2        ,-tg
K,208,0              ,L/2        ,-tg

V,201,202,203,204,205,206,207,208
CYLIND,0,r+(c+c2)*iter,0,-tg,0,90
VSBV,1,5

CYLIND,0,r,0,-tg,0,90

*DO,iii,1,iter,1

CYLIND,r+((c+c2)*(iii-1))+c2,r+((c+c2)*(iii-1))+c2+t+tg,0,-tg,0,90
CYLIND,r+c2+((c+c2)*(iii-1))+t,r+c2+tg+t+((c+c2)*(iii-1)),0,h-tg,0,90
CYLIND,r+c2+t+((c+c2)*(iii-1)),r+c2+c-t+((c+c2)*(iii-1)),h-tg,h,0,90
CYLIND,r+c2+c-t-tg+((c+c2)*(iii-1)),r+c2+c-t+((c+c2)*(iii-1)),0,h-tg,0,90
CYLIND,r+c2+c-t-tg+((c+c2)*(iii-1)),r+c2+c+((c+c2)*(iii-1)),0,-tg,0,90
CYLIND,r+((c+c2)*(iii-1)),r+c2+((c+c2)*(iii-1)),0,-tg,0,90

*ENDDO

NUMMRG,KP,1E-3
/PNUM,VOLU,1
VPLOT

K,5200,0,0,-h-t
```

```
K,5201,0,0,t+h
K,5202,l/2,L/2,t+h
K,5203,l/2,L/2,-h-t

A,5200,5201,5202,5203
VSEL,R,VOLU,,ALL
!VSEL,U,VOLU,,2,4
KSEL,S,KP,,5200
LSLK,S,0
ASLL,S,0
VSBA,ALL,ALL

ET,2,SOLID185
VATT,2,,2
ALLSEL,ALL

NUMMRG,KP,1e-3
ESIZE,10
VMESH,ALL
NUMMRG,NODE,1e-3

INISTATE,SET,MAT,1
INISTATE,DEFINE,,,,,stress,stress
ALLSEL,ALL,ALL

INISTATE,SET,MAT,2
INISTATE,DEFINE,,,,,stress,stress
ALLSEL,ALL,ALL

ASEL,S,AREA,,7
ASEL,A,AREA,,17
ASEL,A,AREA,,12
NSLA,S,1
D,ALL,ALL,0
ALLSEL,ALL,ALL

NSEL,S,LOC,X,0,L/2
NSEL,R,LOC,Y,0,0
NSEL,R,LOC,Z,-tg,t+h
D,ALL,UY,0
ALLSEL,ALL,ALL

NSEL,S,LOC,Y,0,L/2
NSEL,R,LOC,X,0,0
NSEL,R,LOC,Z,-tg,t+h
D,ALL,UX,0
ALLSEL,ALL,ALL

NSEL,S,LOC,X,0,L/2
NSEL,R,LOC,Y,0,L/2
NSEL,R,LOC,Z,t,t
SF,ALL,PRES,press
allsel
```

```
NSEL,S,LOC,X,0,L/2
NSEL,R,LOC,Y,0,L/2
NSEL,R,LOC,Z,t+h,t+h
SF,ALL,PRES,press
ALLSEL,ALL

FINISH
/SOL
ANTYPE,STATIC,NEW                 ! Static analysis
NLGEOM,ON   !non-linearities
NCNV,,1E20
KBC,0
TIME,press
*SET,nm,node(0,0,0)
MONITOR,1,nm,uz
OUTRES,all,all !write the result at every step
NSUBST,nb,400,nb
NEQIT,800
SOLVE
FINISH

/POST26
NSOL,2,nm,U,Z
/axlab,y,Displacement (um)
/AXLAB,x,Pressure (Pa)
PLVAR,2
FINISH
```

11.5.3 One layer homogenized: Modal analysis

Modular parameters
- Length: L
- Thickness: t
- Prestress homogenized: stress
- Number of corrugation: iter
- Width of the corrugation : c
- Height of the corrugation : h
- Space between two corrugations : c2
- Position of the first corrugation : r

```
FINISH
/CLEAR

/UNITS,uMKS

*SET,anchor,25
*SET,t,80e-3
*SET,l,1e3
*SET,stress,-50
r=29
c=10
h=5
iter=2
c2=5

/PREP7

MP,EX,1,123e3
MP,NUXY,1,0.275
MP,DENS,1,3046e-18


K,001,0                  ,0                ,0
K,002,L/2                ,0                ,0
K,003,L/2+anchor         ,0                ,0

K,011,0                  ,L/2              ,0
K,012,L/2                ,L/2              ,0
K,013,L/2+anchor         ,L/2              ,0

K,021,0                  ,L/2+anchor       ,0
K,022,L/2                ,L/2+anchor       ,0
K,023,L/2+anchor         ,L/2+anchor       ,0

K,101,0                  ,0                ,t
K,102,L/2                ,0                ,t
K,103,L/2+anchor         ,0                ,t

K,111,0                  ,L/2              ,t
K,112,L/2                ,L/2              ,t
K,113,L/2+anchor         ,L/2              ,t
```

```
K,121,0                    ,L/2+anchor        ,t
K,122,L/2                  ,L/2+anchor        ,t
K,123,L/2+anchor           ,L/2+anchor        ,t


/vup,1,z
/VIEW,1,1,-1,1
/PNUM,KP,1
KPLOT

*DO,k,0,000,100
*DO,j,0,10,10
*DO,i,0,1,1
V,1+i+j+k,2+i+j+k,12+i+j+k,11+i+j+k,101+i+j+k,102+i+j+k,112+i+j+k,111+i+j+kvplot
*ENDDO
*ENDDO
*ENDDO
VPLOT


CYL4,0,0,0,0,r+(c+c2)*iter,90,t
VSBV,1,5
CYLIND,0,r,0,t,0,90

ALLSEL,ALL

*DO,iii,1,iter,1

CYLIND,r+((c+c2)*(iii-1)),r+((c+c2)*(iii-1))+c2,0,t,0,90
CYLIND,r+c2+((c+c2)*(iii-1)),r+(c+c2)+((c+c2)*(iii-1)),h,t+h,0,90
CYLIND,r+c2+((c+c2)*(iii-1)),r+t+c2+((c+c2)*(iii-1)),0,t,0,90
CYLIND,r+c2+((c+c2)*(iii-1)),r+t+c2+((c+c2)*(iii-1)),t,h,0,90
CYLIND,r+c2-t+c+((c+c2)*(iii-1)),r+c2+c+((c+c2)*(iii-1)),t,h,0,90
CYLIND,r+c2-t+c+((c+c2)*(iii-1)),r+c2+c+((c+c2)*(iii-1)),0,t,0,90

*ENDDO

NUMMRG,KP,1E-3
/PNUM,VOLU,1
VPLOT

K,5200,0,0,-h-t
K,5201,0,0,t+h
K,5202,l/2,L/2,t+h
K,5203,l/2,L/2,-h-t


A,5200,5201,5202,5203
VSEL,S,VOLU,,ALL
VSEL,U,VOLU,,2,4
KSEL,S,KP,,5200
LSLK,S,0
ASLL,S,0
VSBA,ALL,ALL
```

```
ALLSEL,ALL

NUMMRG,KP,1E-3
/PNUM,VOLU,1
VPLOT

ET,1,SOLID185
KEYOPT,1,2,2
VATT,1,,1

ESIZE,10
VMESH,ALL
NUMMRG,NODE,1e-3

INISTATE,SET,MAT,1
INISTATE,DEFINE,,,,,stress,stress
ALLSEL,ALL,ALL


ASEL,S,AREA,,7
ASEL,A,AREA,,17
ASEL,A,AREA,,12
NSLA,S,1
D,ALL,ALL,0
ALLSEL,ALL,ALL

NSEL,S,LOC,X,0,L/2
NSEL,R,LOC,Y,0,0
NSEL,R,LOC,Z,0,t+h
D,ALL,UY,0
ALLSEL,ALL,ALL

NSEL,S,LOC,Y,0,L/2
NSEL,R,LOC,X,0,0
NSEL,R,LOC,Z,0,t+h
D,ALL,UX,0
ALLSEL,ALL,ALL

FINISH
/SOLU
ANTYPE,STATIC,NEW                ! Static analysis
PSTRESS,ON
SOLVE
FINISH

/POST1
/DSCALE,ALL,1
/CONTOUR,ALL,128
PLNSOL,U,Z
FINISH

/SOL
ANTYPE,MODAL          ! Modal analysis
MODOPT,LANB,5,1e4     ! Select eigensolver
```

```
MXPAND,5                ! Specify the number of modes to expand, if desired.
PSTRESS,ON
SOLVE
FINISH

/POST1
/DSCALE,ALL,AUTO
/CONTOUR,ALL,128
SET,FIRST
```

11.5.4 One layer homogenized: Static analysis

Modular parameters

- Length: L
- Thickness: t
- Prestress homogenized: stress
- Applied pressure : press
- Number of pressure step : nb
- Number of corrugation: iter
- Width of the corrugation : c
- Height of the corrugation : h
- Space between two corrugations : c2
- Position of the first corrugation : r

```
FINISH
/CLEAR

/UNITS,uMKS

*SET,anchor,25
*SET,t,80e-3
*SET,l,1e3
*SET,stress,-50
*SET,press,20E-6
r=29
c=10
h=5
iter=2
c2=5
nb=200
/PREP7


MP,EX,1,123e3
MP,NUXY,1,0.275
MP,DENS,1,3046e-18


K,001,0                     ,0              ,0
K,002,L/2                   ,0              ,0
K,003,L/2+anchor            ,0              ,0

K,011,0                     ,L/2            ,0
K,012,L/2                   ,L/2            ,0
K,013,L/2+anchor            ,L/2            ,0

K,021,0                     ,L/2+anchor     ,0
K,022,L/2                   ,L/2+anchor     ,0
K,023,L/2+anchor            ,L/2+anchor     ,0

K,101,0                     ,0              ,t
K,102,L/2                   ,0              ,t
K,103,L/2+anchor            ,0              ,t
```

```
K,111,0                  ,L/2            ,t
K,112,L/2                ,L/2            ,t
K,113,L/2+anchor         ,L/2            ,t

K,121,0                  ,L/2+anchor     ,t
K,122,L/2                ,L/2+anchor     ,t
K,123,L/2+anchor         ,L/2+anchor     ,t



/vup,1,z
/VIEW,1,1,-1,1
/PNUM,KP,1
KPLOT

*DO,k,0,000,100
*DO,j,0,10,10
*DO,i,0,1,1
V,1+i+j+k,2+i+j+k,12+i+j+k,11+i+j+k,101+i+j+k,102+i+j+k,112+i+j+k,111+i+j+kvplot
*ENDDO
*ENDDO
*ENDDO
VPLOT

CYL4,0,0,0,0,r+(c+c2)*iter,90,t
VSBV,1,5
CYLIND,0,r,0,t,0,90

ALLSEL,ALL

*DO,iii,1,iter,1

CYLIND,r+((c+c2)*(iii-1)),r+((c+c2)*(iii-1))+c2,0,t,0,90
CYLIND,r+c2+((c+c2)*(iii-1)),r+(c+c2)+((c+c2)*(iii-1)),h,t+h,0,90
CYLIND,r+c2+((c+c2)*(iii-1)),r+t+c2+((c+c2)*(iii-1)),0,t,0,90
CYLIND,r+c2+((c+c2)*(iii-1)),r+t+c2+((c+c2)*(iii-1)),t,h,0,90
CYLIND,r+c2-t+c+((c+c2)*(iii-1)),r+c2+c+((c+c2)*(iii-1)),t,h,0,90
CYLIND,r+c2-t+c+((c+c2)*(iii-1)),r+c2+c+((c+c2)*(iii-1)),0,t,0,90

*ENDDO

NUMMRG,KP,1E-3
/PNUM,VOLU,1
VPLOT

K,5200,0,0,-h-t
K,5201,0,0,t+h
K,5202,l/2,L/2,t+h
K,5203,l/2,L/2,-h-t

A,5200,5201,5202,5203
VSEL,S,VOLU,,ALL
VSEL,U,VOLU,,2,4
KSEL,S,KP,,5200
```

```
LSLK,S,0
ASLL,S,0
VSBA,ALL,ALL
ALLSEL,ALL

NUMMRG,KP,1E-3
/PNUM,VOLU,1
VPLOT

ET,1,SOLID185
KEYOPT,1,2,2
VATT,1,,1

NUMMRG,KP,1e-3
ESIZE,10
VMESH,ALL
NUMMRG,NODE,1e-3

INISTATE,SET,MAT,1
INISTATE,DEFINE,,,,,stress,stress
ALLSEL,ALL,ALL

ASEL,S,AREA,,7
ASEL,A,AREA,,17
ASEL,A,AREA,,12
NSLA,S,1
D,ALL,ALL,0
ALLSEL,ALL,ALL

NSEL,S,LOC,X,0,L/2
NSEL,R,LOC,Y,0,0
NSEL,R,LOC,Z,0,t+h
D,ALL,UY,0
ALLSEL,ALL,ALL

NSEL,S,LOC,Y,0,L/2
NSEL,R,LOC,X,0,0
NSEL,R,LOC,Z,0,t+h
D,ALL,UX,0
ALLSEL,ALL,ALL

NSEL,S,LOC,X,0,L/2
NSEL,R,LOC,Y,0,L/2
NSEL,R,LOC,Z,t,t
SF,ALL,PRES,press
allsel

NSEL,S,LOC,X,0,L/2
NSEL,R,LOC,Y,0,L/2
NSEL,R,LOC,Z,t+h,t+h
SF,ALL,PRES,press
ALLSEL,ALL

FINISH
```

```
/SOL
ANTYPE,STATIC,NEW                    ! Static analysis
NLGEOM,ON   !non-linearities
NCNV,,1E20
KBC,0
TIME,press
*SET,nm,node(0,0,0)
MONITOR,1,nm,uz
OUTRES,all,all !write the result at every step
NSUBST,nb,400,nb
NEQIT,800
SOLVE
FINISH

/POST26
NSOL,2,nm,U,Z
/axlab,y,Displacement (um)
/AXLAB,x,Pressure (Pa)
PLVAR,2
FINISH
```