ANALYSIS OF THE SPACER GRIDS STIFNESS INFLUENCE IN THE DETERMINATION OF THE NATURAL FREQUENCIES OF NUCLEAR PLANTS FUEL ASSEMBLIES

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Abstract. *The objective of this work is to evaluate the spacer grids stiffness influence in the fuel assemby stiffness and natural frequencies, using the finite element method applied to computational simulation (Ansys, 1994). The spacer grid modeling uses beam elements with equivalent structural characteristics of the inconel straps. The fuel assembly finite element model is built to determinate the fuel assemblies natural frequencies and stiffness and it contains the eight spacer grids, the fuel rods, the guide thimbles, the top nozzle and the bottom nozzle. The results of fuel assembly stiffness are obtained considering the spacer grids rigid, in a first time, and then with it real flexibility. Those results are compared between themselves. The results of fuel assembly natural frequencies are corrected by considering the fuel rods sliding and compared to experimental data. The fuel assembly finite element model shows good agreement with experimental data.*

Keywords: *natural frequencies, stiffness, finite element, spacer grids, fuel assembly, nuclear plants.*

1. Introduction

The Brazilian nuclear plants use pressurized water reactors and one of its more important components is the fuel assembly because in it is the uranium under the form of the UO_2 syntherized tablets responsible by nuclear fission and energy liberation.

The fuel assembly is an arrangement of fuel rods containing uranium, mounted how a spaced and reticulate bundle, according Fig.1 (Carrilho, 2000). In Figure 2 is illustrated the spacer grids of the fuel assemblies.

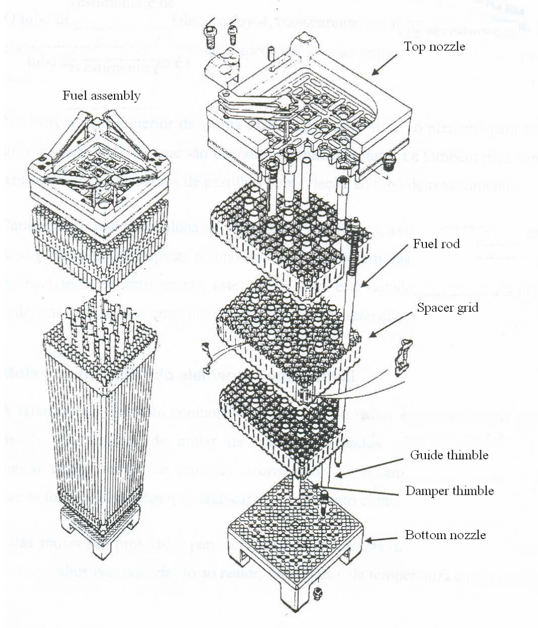


Figure 1. Fuel assembly and its components

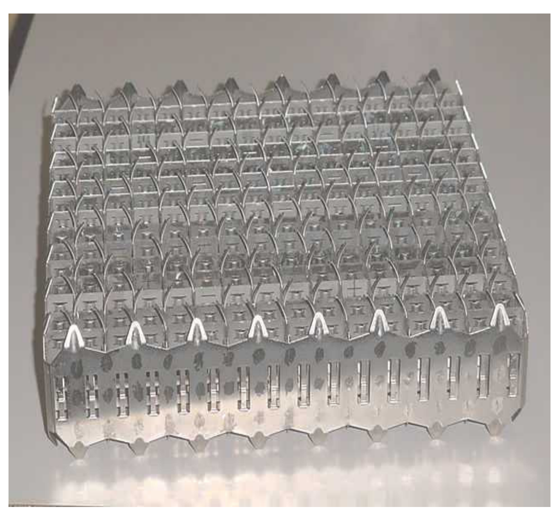


Figure 2. Spacer grids of fuel assemblies

This bundle is suported by spacer grids, separated and fixed by guide thimbles. Thus the spacer grids are very important to the fuel assembly structural stability. The fuel assembly finite element model proposed by Carrilho (2000) and Carrilho *et al.* (2000) doesn't consider the spacer grids geometry and its effect on the fuel assembly natural frequencies and stiffness. For this reason, the present model incorporates the spacer grid geometry in order to evaluate its influence upon the fuel assembly structural behavior and natural frequencies.

The first step of this work consists in the study of the structural behavior of the spacer grids, using the Ansys program release 8.1. This study include the modeling of spacer grids, using beam elements with equivalent structural behavior to inconel 718 straps, determination of spacer grids stiffness.

The second step of this work consists in the study of the fuel assemblies structural behavior with the incorporation of the spacer grids through determination of the natural frequencies and mode shapes, determination of the maximum and minimum lateral stiffness.

2. Modeling and study of the spacer grids structural behavior

The study of the structural behavior of the spacer grids through finite element method include the determination of the stiffness of the spacer grids springs and dimples that constitute each inner cell of this grid by geometric nonlinear elastic and static analysis, modeling of the spacer grids using beam elements with structural behavior equivalent to inconel straps and spacer grids stiffness determination Jeon *et al.* (2001), Park *et al.* (2003) and Yoon *et al.* (2001). The model of inner wall of the spacer grid with the elastic and quadrilateral element SHELL 63 (Ansys, 1994) require 1295 elements while the model with the elastic element BEAM 4 (Ansys, 1994) require only one element.

2.1. Determination of the springs and dimples stiffness

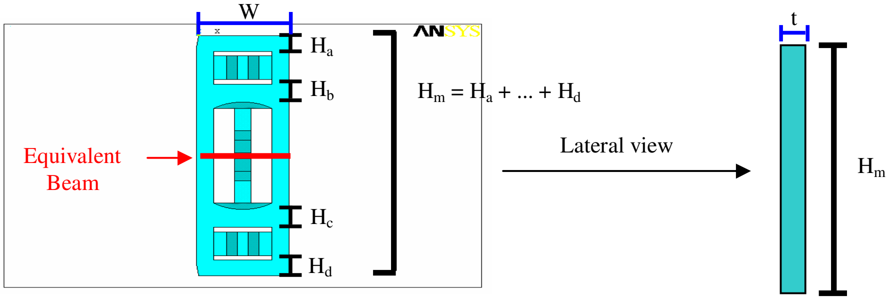
In the determination of the springs stiffness are imposed on the springs displacements equals to 0.001 m in the global Z direction and only the spring movements are permitted, according to Fig. 3 (a). The dimples stiffness determination, is similar to previous determination but the displacements are imposed on the dimples and only the dimples movements are permitted.

(a) Stiffness of the springs (b) Stiffness of the dimples

P: $U_X = U_Y = U_Z = Rot_X = Rot_Y = Rot_Z = 0$ (Movements restrictions)

Figure 3. Models to determination of springs and dimples stiffness

The use of shell elements provides better results than beam elements, although the computational effort is greater. However, if the beam element used represents the structure equivalently the computational effort is lower and the results tend to approximate to experimental values. Based on this fact and in the maximum number of elements / nodes (equals to 32000) of the Ansys academic version limit, the spacer grids inner components, fuel rods and guide thimbles are modeled using beam elements. Therefore is used the equivalent stiffness concept to the beam elements, according Fig.4.



(a) (b)

Figure 4. (a) Modeling of the spacer grid with beam elements. (b) Equivalent spacer grid wall cross-section area.

Where:

H_a, H_b, H_c, H_d, H_m: Height, in m, of the spacer grids wall.

W, t: Width and thickness, respectively, of the spacer grids inner wall. These values are constants.

To the beam element, the Eq. 1 represents the concept of the equivalent stiffness

$$K_{eq}=EA_{eq}/W \tag{1}$$

Where:

K_{eq}: Axial equivalent stiffness, in N/m.

E: Young's Module, in Pa, to Inconel 718.

A_{eq}: Equivalent cross - section area, in m².

W: Width, in m.

The beam equivalent cross – section area consider only the portion of the spacer grid wall that contains area, disregarding the wall vain where are localized the springs and dimples. Thus the cross-section area is given according Eq. 2.

$$A_{eq}=H_m t \tag{2}$$

Thus, Eq. 1 can be rewrite:

$$K_{eq}=[E(H_m t)/W] \tag{3}$$

To considering the symmetry of the fuel assembly the instrumentation thimble is replaced for one fuel rod and the spacer grid have 236 cells to insertion of fuel rods and 20 cells to insertion of guide thimbles. Another consideration is the replacement of the guide thimbles close to spacer grid half portions. Thus the spacer grid is symmetric in the longitudinal and transversal directions, according Fig. 5.

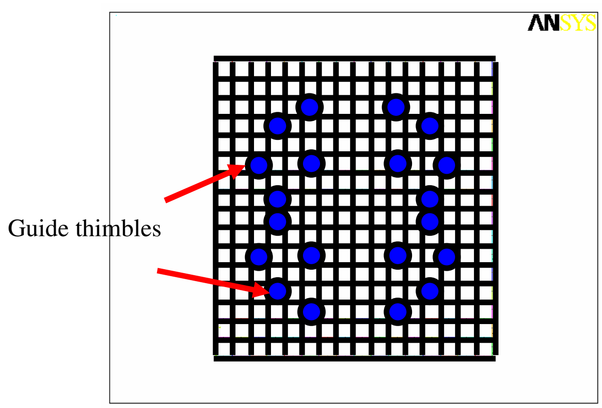
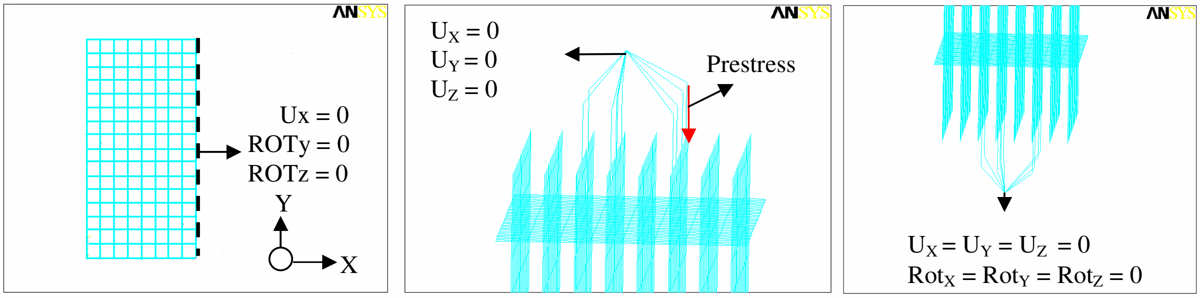


Figure 5. Guide thimbles disposed symmetrically on the spacer grids

3. Modeling and study of the fuel assembly structural behavior

The modeling of the fuel assembly considers only the eight spacer grids, 118 fuel rods and 10 guide thimbles. Besides because of limitation of element number by Ansys program (academic version), the model is reduced to ½ symmetry. The 118 fuel rods and 10 guide thimbles are modeled by beam elements and the nozzles, top and bottom, are represented by one node respectively. To the top nozzle is considered the force of the PWR holding spring through loads applied in the guide thimbles. In Figure 6 is showed the spacer grid and the discretization of the nozzles. The node that represents the bottom nozzle have all the movements restricted and the node that represents the top nozzle are permitted only rotations in the x, y and z directions. The mass is added directly to beams that represents the fuel rods.



(a) Symmetry of grids (b) Top nozzle (c) Bottom nozzle

Figure 6. Spacer grid symmetry and nozzle discretization

3.1. Determination of fuel assembly natural frequencies

With the fuel assembly model is realized the modal analysis to determination of natural frequencies. To adjust the model the spacer grids are considered rigid by the increase of the Young's module in 10000 times and is realized a modal analysis. After the adjusting of the model is considered the actual spacer grids Young's module and another modal analysis is realized. All the modal analysis considers the PWR holding spring prestress effect.

3.2. Determination of the fuel assembly maximum lateral stiffness

After the modal analysis the fourth spacer grid shows higher displacements and forces varying between 0.1 N and 1.0 N are applied in this grid to determination of fuel assembly maximum lateral stiffness.

3.3. Determination of the fuel assembly minimum lateral stiffness and correction of the natural frequencies

The minimum stiffness of the fuel assembly is characterized by sliding of fuel rods through the unit force applied in the fourth spacer grid make possible lager displacement of the fuel assembly. The analysis are nonlinear, elastic and static and are added the nonlinear springs combination element COMBIN 40 (Ansys, 1994) with different degrees of freedom to reproduce the fuel rods behavior into the spacer grids cells. In Figure 7 are showed the discretization of the one spacer grid inner cell and sliding criteria. To cell that contains the guide thimbles are maintained the rigid beams. Each COMBIN 40 element has one degree of freedom per node and is require attributing U_X, U_Y, U_Z and Rot_Z to the fuel rods. This attribution is made by superposition of these elements with each specific degree of freedom.

(a) Spacer grid inner cell (b) Finite element model

Figure 7. Discretization of the spacer grid inner cell

The sliding occurs when are exceeded the adherence force that maintain the fuel rod in it initial positions. The determination of this force is given by Eq. 4, 5 and 6.

$$F = \mu N \tag{4}$$

$$N = K_{eq}\delta \tag{5}$$

$$1/K_{eq} = 1/K_1 + 1/K_2 \tag{6}$$

The natural frequencies correction is given by average stiffness, according to Eq.7.

$$K_{av} = (K_{max} + K_{min})/2 \tag{7}$$

The natural frequencies correction factor, β (Carrilho, 2000), is obtained by relationship between K_{max} e K_{av} according to Eq. 8.

$$K_{av}=\beta\ K_{max} \tag{8}$$

Thus, the natural frequencies equation is given according to Eq.9.

$$\omega = \lambda(K_{max}/M)^{1/2} \tag{9}$$

The corrected natural frequencies equation is given to Eq. 10.

$$\Omega = \lambda(K_{av}/M)^{1/2} \tag{10}$$

The substitution of (8) into (10) provides the relationship between the natural frequencies obtained by maximum lateral stiffness and the corrected natural frequencies according to Eq. 11.

$$\Omega = (\beta)^{1/2}\ \omega \tag{11}$$

Where:

ω: Fuel assembly natural frequencies, in Hz.
M: Fuel assembly mass, in Kg.
K_{av}: Fuel assembly average stiffness, in N/m.
K_{max}: Fuel assembly maximum lateral stiffness, in N/m.
K_{min}: Fuel assembly minimum lateral stiffness, in N/m.
β: Natural frequencies correction factor.
Ω: Fuel assembly corrected natural frequencies, in Hz.
F: Adherence force, in N.
μ: Inconel friction coefficient.
N: Force normal component, in N.
K_{eq}: Spring-dimple equivalent stiffness, in N/m.
δ: Spring displacement by fuel rod insertion, in m.
K_1: Spacer grid spring stiffness, in N/m.
K_2: Spacer grid dimple stiffness, in N/m.
λ: Eigenvalue associated factor

4. Results

In Table 1 the results obtained to the spacer grid springs and dimples stiffness are showed and compared to experimental results (Carrilho, 2000). This determination is realized from nonlinear, elastic and static analysis by geometric nonlinearity considerations and the results approximates to experimental results. .

Table 1 Stiffness of spacer grids springs and dimples

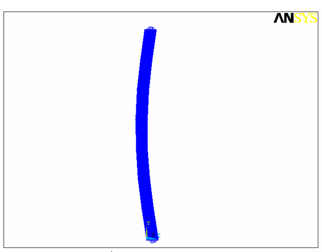
Stiffness of inconel spring(N/m)		Stiffness of inconel dimple(N/m)	
Experimental result	163920	Experimental result	419600
Numerical result	162740	Numerical result	425330

The spacer grid stiffness increases when the line number increases and it can justified by the equivalent stiffness concept analyzing the spacer grid how a set of springs, in parallel, with identical value of stiffness. Therefore the value of spacer grid stiffness is 64892400 N/m. The spacer grids stiffness decreases when the column number increases and it can be explained by the axial stiffness of the spacer grids wall. Using the model of fuel assembly, considering the spacer grids geometry is realized a linear, elastic and static analysis to calculate the holding spring prestress effect to the guide thimbles connected to top nozzle. The total prestress value is 7100 N and to each one of the ten guide thimble this value is 355 N. After to calculate the prestress effect is realized the modal analysis to obtain the natural frequencies. In Table 2 are showed the natural frequencies results comparing to experimental results (Carrilho, 2000).

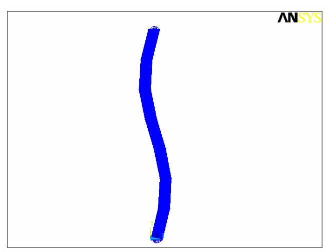
Table 2 Fuel assembly natural frequencies

Frequencies(Hz)	1st	2nd	3rd	4th	5th	6th
Experimental results	3.4	6.9	10.9	16.2	21.4	27.5
Rigid grids results	4.35	9.48	14.78	20.24	25.60	29.86
Flexible grids results	4.24	9.31	14.59	20.05	25.45	29.80

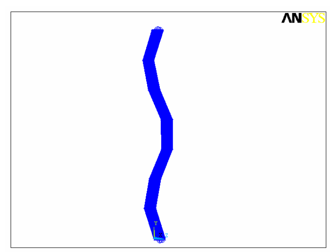
The modes shape obtained to both models are identical because the boundary conditions are identical. In Figure 8 are showed the modes shape to fuel assembly.



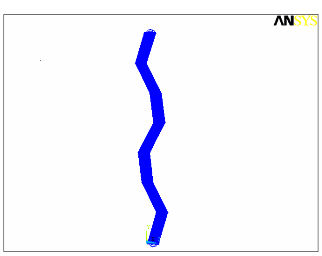
(a) 1st Mode shape



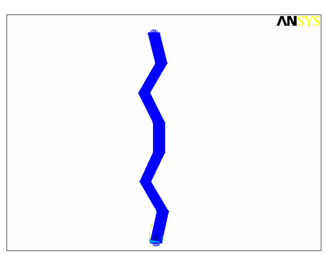
(b) 2nd Mode shape



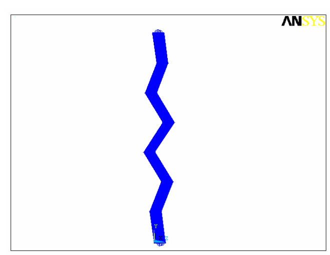
(c) 3rd Mode shape



(d) 4th Mode shape



(e) 5th Mode shape



(f) 6th Mode shape

Figure 8. Fuel assembly modes shape

The natural frequencies determination shows the higher displacement in the fourth spacer grid and the determination of the fuel assembly stiffness is realized applying an unit force in this grid. In Figure 9 are showed the results of the maximum stiffness to the fuel assembly.

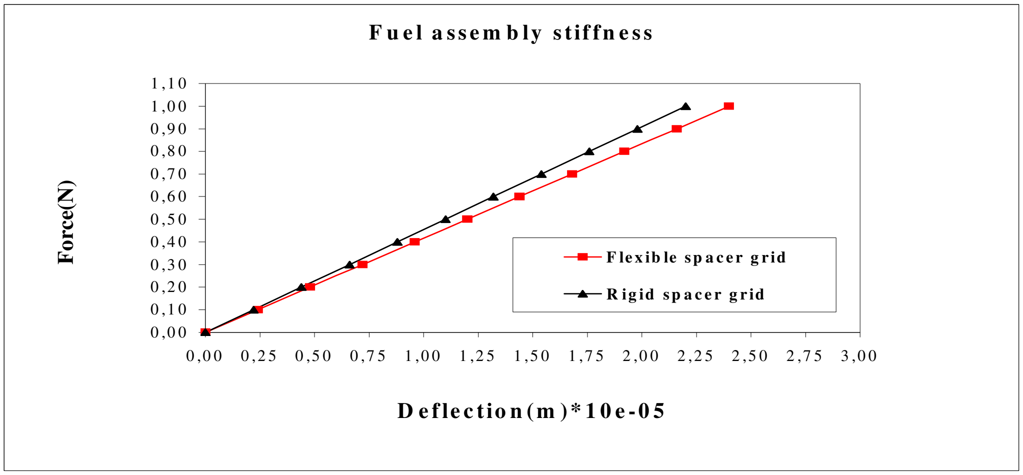


Figure 9. Maximum fuel assembly stiffness

The guide thimbles are the structural components that supports the higher loads, according to Fig. 10 and it represents an obstacle to the sliding of the fuel rods. This obstacle is a combination of the prestress imposed by holding spring and the rigid conection between guide thimbles and spacer grid. Thus is characterized the fact of the fuel rods sliding to occur in rank. The fuel rods localized in the spacer grids board ranks firstly and the spacer grids localized in the more internal regions have difficulted slidings because the guide thimbles presence. Thus the natural sliding is represented by line with slope K_1, according to Fig. 11. The factor β is calculated by K_1, according to Table 3 and the corrected natural frequencies are given in Table 4 in comparison with experimental results (Carrilho, 2000).

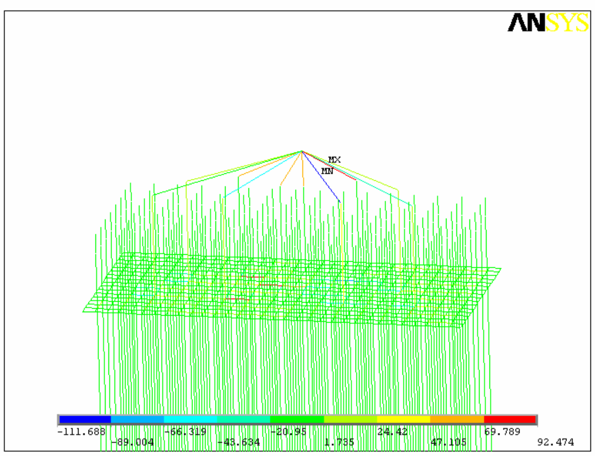


Figure 10. Guide thimbles supported forces

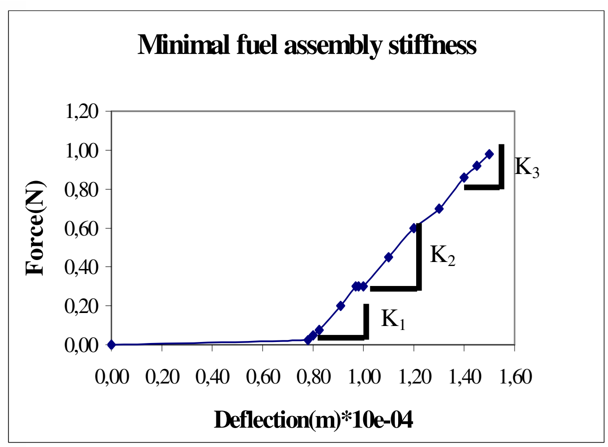


Figure 11. Fuel rods sliding

Table 3Determination of the β factor

Maximum stiffness(N/m)	83333
Minimum stiffness(N/m)	13500
Average stiffness(N/m)	55166.5
β	0.66
√β	0.81

Table 4 Fuel assembly natural frequencies

Corrected fuel assembly natural frequencies						
Frequencies(Hz)	1^{st}	2^{nd}	3^{rd}	4^{th}	5^{th}	6^{th}
Experimental results	3.4	6.9	10.9	16.2	21.4	27.5
Flexible grids results	3.43	7.54	11.82	16.24	20.61	24.14

5. Material properties and geometry data

The zircaloy and inconel mechanical properties at 25°C (Software Cambridge Engineering Selector, 2004) are given in Table 5. The fuel rods and guide thimbles geometry data are given in Table 6.

Table 5 Mechanical properties

Materials Properties		
Properties	Inconel 718	Zircaloy
Young's Module(Pa)	2*e11	1*e11
Specific mass(Kg/m³)	8300	9309.5
Friction coefficient	-	0.35
Poisson's coefficient	0.3	0.35

Table 6 Fuel rods and guide thimbles geometry data

Fuel rods and guide thimbles dimensions		
Dimensions	Guide thimbles	Fuel rods
Length(m)	3.985	3.85
External diameter(m)	0.01196	0.0095
Internal diameter(m)	0.01105	0.00822
Cross-section(m²)	1.64*e-05	1.781*e-05

6. Conclusions

Consideration of beam equivalent structural behavior makes possible satisfactories results and reproduces the real inconel straps structural behavior. The spacer grids confer to the fuel assembly model flexibility and the results are more accurate. The fuel rods sliding consideration permit the natural frequencies correction and the results approximates to experimental results.

7. Acknowledgements

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8. References

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9. Responsibility notice