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Modal Analysis of Nuclear Fuel Assembly using the Model Reduction Method

Muhammad Subhan and Namgung Ihn*
KEPCO International Nuclear Graduate School (KINGS)
658-91 Haemaji-ro, Seosaeng-myeon, Ulju-gun, Ulsan 45014, Republic of Korea.
**Corresponding author: inamgung@kings.ac.kr*

1. Introduction

Nuclear fuel assemblies used in pressurized water reactors, PWR, are composed of metallic components and fuel rods containing uranium pellets, assembled as a spaced and reticulate bundle. This structure includes bottom and top nozzles, hold-down spring, spacer grids, and guide thimbles, and all of them are connected by welding and mechanical joints (screws or bulges). Park et al. (2009) [1] stated that the fuel design should be conceived with an adequate lateral stiffness for accident loads, such as a seismic activity or a loss of coolant accident (LOCA). One of the design objectives of nuclear fuel assembly is maintaining not only for static structural integrity but also for dynamic integrity. Each component of fuel assembly plays a specific role in the mechanical performance of the nuclear fuel, for example, spacer girds maintain spaces between fuel rods adequately and keep the fuel rod on the bottom of fuel assembly.

Historically Korean-peninsula had been regarded as earthquake-free; however, after Fukushima accident in 20111, seismic integrity becomes a concern and important issue. Since nuclear fuel assembly is the source of high level radio-active material release, we need to prove that fuel assembly will not break for certain level of seismic loading. There are two method to assess fuel assembly integrity; one using modal-spectrum analysis and the other using time-history analysis. For the modal-spectrum analysis, modal analysis of reactor system as a whole is required. For this goal, the first step is assessing dynamic integrity of fuel assembly by evaluating natural vibration characteristics of single fuel assembly. This study reviewed the modal analysis of the fuel assembly, the fuel assembly modeling that reflects the latest advances in computer technology for 3D dynamic simulation. In particular, the reduced model of the fuel assembly for natural frequency will be investigated. As far as authors are concerned, the development of 3D model of nuclear fuel for APR 1400 was not done and instead 2D model were used.

In this research, a 3D modeling approach will be introduced and proposed the method and will carry out a simple case of dynamic analysis. In this research, beam and shell elements are using to construct fuel assembly and reduce model size. The modal analysis of this fuel assembly gives mode shapes and modal values. The modal value represent natural frequencies of fuel assembly. The model shape reveals deformation behavior according to modal value, hence, we can approximate which part will take mode load and get dynamic stress.

2. Method and Result

This chapter describes the method and results of the fuel assembly modeling, analysis issues, and interpretation of analysis results.

2.1 Nuclear fuel assembly components

The reactor core is composed of 241 fuel assemblies and 93 control element assemblies (CEAs). The fuel assemblies have arranged to approximate a right circular cylinder with an equivalent diameter of 3,647 mm (143.6 in) and an active length of 3,810 mm (150 in). The fuel assembly, which provides for 236 fuel rod positions (16 × 16 array), includes four guide tubes and one instrument tube welded to spacer grids.

The fuel assembly, when installed into reactor core, is compressed at the top and supported by lower end fitting. Each guide tubes displaces four fuel rod positions and provides channels that guide the CEA rod over their entire length of travel. In-core instrumentation (ICI) has been installed in the instrument tube of selected fuel assemblies. The ICI was routed into the bottom of the fuel assemblies through the bottom head of the reactor vessel. The fuel assemblies and the material specification for APR 1400 shows in figure 1.

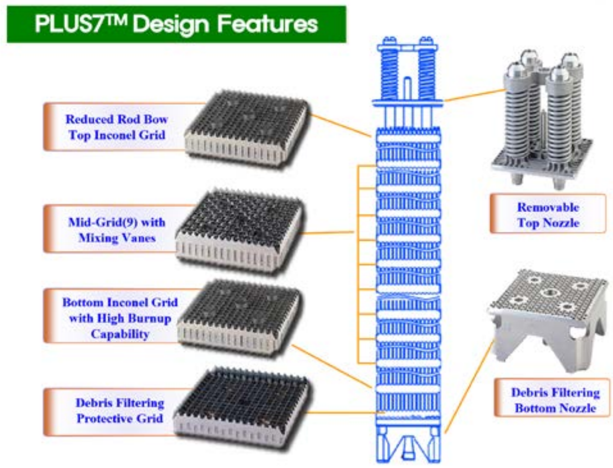

Fig 1. Nuclear fuel assembly component of APR 1400

2.2 Orthotropic material

In material science and solid mechanics, orthotropic materials have material properties that differ along three mutually-orthogonal twofold axes of rotational symmetry at a particular point. They are a subset of anisotropic materials because their properties change when measured from different directions. Orthotropic material is part of anisotropic material that depends on the direction of measurement. Orthotropic materials have three perpendicular planes/axes of symmetry. Anisotropic material, in contrast, has the properties depend on directions. Isotropic materials have homogeneous material property in all direction.

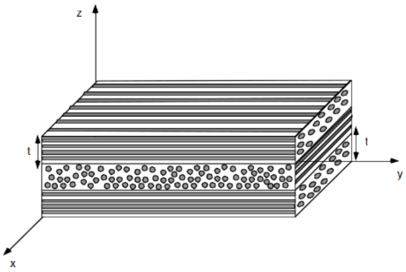

Figure 2. Orthotropic direction

In figure 2, the properties are different in all three orthogonal directions. By similar reasoning to that applied to the transversely isotropic case, it requires nine independent elastic constants to define an orthotropic material such as young's modulus, shear Modulus, and independent Poisson's ratio [2].

2.3 Equivalent material properties of 3D model and beam-shell model.

Comparing Figure 1 and Figure 6, the spacer grid was not accurately modeled to the real spacer grid. This is to simplify spacer grid model and get reduce problem size and also eliminates spurious local vibration mode. In this case, the properties of the material of the shell-beam model have deviated from real isotropic material due to the change of simplification of geometry. For dynamic analysis, it is important to keep the mass conservation principle while stiffness can be adjusted to make the whole system behave similarly to the test.

In this research, for the simplicity, we assume the material properties of spacer grid and lower end fitting model follows orthotropic properties. Hence, the material parameters of X and Z directional Young's modulus were set as variable. The figure shell model of the lower end fitting and beam model of the spacer grid shows in fig 5 and fig 6. Based on data from Subhan (2020) [3], we know that the deformation of lower end-fitting was about 0.043647 mm. This value for reference to making optimization of lower end-fitting of the shell model using ANSYS software [4].

Because spacer grid and lower end fitting and upper end fitting were modeled as beam, shell and shell, we changed geometry and as a result we need to find equivalent material properties that will make reduced model behave similar to the full model.

As an example, lower end fitting was modeled as shell, see figure 5, and the material properties are adjusted as follows.

19	Orthotropic Elasticity		
20	Young's Modulus X direction	3.66E+10	Pa
21	Young's Modulus Y direction	3.37E+10	Pa
22	Young's Modulus Z direction	3.1E+10	Pa
23	Poisson's Ratio XY	0.27	
24	Poisson's Ratio YZ	0.27	
25	Poisson's Ratio XZ	0.27	
26	Shear Modulus XY	2E+10	Pa
27	Shear Modulus YZ	2.1E+10	Pa
28	Shear Modulus XZ	2.2E+10	Pa
29	Multilinear Isotropic Hardening	Tabular	
30	Scale	1	
31	Offset	0	Pa

Fig 3. Parameter set of properties

We use material properties from the default material data base then modifies it. The material properties of lower end-fitting are based on ANSYS material properties [5]. The resulting optimization of lower end-fitting shows in figure 4. All nuclear fuel assembly components such as mid spacer grid, debris spacer grid, top and bottom spacer grid made of Zircaloy has been set by the same process to obtain material optimization. Material properties of the nuclear fuel assembly shown in table 1.

Optimization , Candidate Points

B	C	D	E	F
Name	P9 - Young's Modulus X direction (Pa)	P10 - Shear Modulus XY (Pa)	P8 - Directional Deformation Minimum (mm)	P11 - Output Parameter Value
Candidate Point 1	3.8125E+10	2.2167E+10	-0.048549	0.00011031
Candidate Point 2	3.8125E+10	2.2171E+10	-0.048546	0.00011298
Candidate Point 3	3.8125E+10	2.2199E+10	-0.048527	0.00013205

Fig 4. Schematic candidate point of shell model

Table 1. Material properties of nuclear fuel assembly

Component	Material
Top end-fitting Lower end-fitting	Stainless steel 304
Debris spacer grid Top grid Bottom grid	Inconel 718
Guide tube Instrument tube 9 Mid grids	Zircaloy

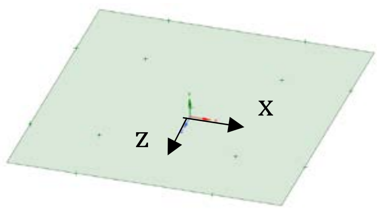

Fig 5. Shell model of lower end fitting

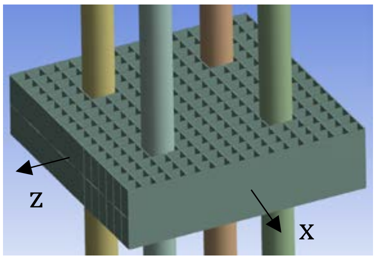

Fig 6. Beam model of spacer grid

2.4 Nuclear fuel assembly boundary condition

Particularly for the dynamic response of fuel assembly, due to the complicated structure, the degree of freedom of the 3D model will be too large and which is not necessary. Due to this reason, model reduction by using beam and shell elements is essential. The construction of the 3D model using beam and shell elements will present in this research. The model of the nuclear fuel assembly in ANSYS software from 3D geometry of each component has been changed to shell and beam model and also material properties from isotropic to the orthotropic material.

We should consider reflecting the structural effects of the lower end-fitting due to a mass come from the weight of a nuclear fuel assembly. Also, the hold-down plate is movable, acts on the underside of the extended tubes of the upper guide structure, and is loaded by hold-down spring [6]. There is fixed-support in the lower end-fitting leg and the guide-post at the top due to the extended upper guide structure. The beam profile for each component and boundary condition of the nuclear fuel assembly is present in table 2 and figure 7.

Table 2. Beam Profile Fuel Assembly Component

Name	Beam Profile
Guide tube	Outer diameter = 26 mm Inner diameter = 24 mm
Guide post	Outer diameter = 17 mm Inner diameter = 14 mm
Spacer Grid	Thickness = 1mm Area= 53.5 x 53.5 mm

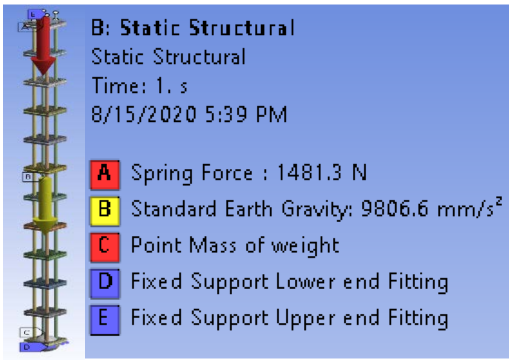

Fig 7. Boundary condition of nuclear fuel assembly

2.5 Results of modal analysis

Modal analyses for in-air and in-water cases have been carrying out to verify that the fuel assembly detailed model gives correct information on natural frequencies and mode shapes. The immersion of the fuel assembly in water was model by adding a fictitious mass to the various components of the fuel assembly [7]. But for this research, we are focus on modal analysis in the air.

To get modal analysis in the ANSYS software, we have been setting the number of modal analysis for 20 modes. The modal analysis of lower end-fitting has combined with the static analysis. It's needed to get a more closed situation like in the core of the reactor. To validate our results, we should compare the testing result of a nuclear fuel assembly [1]. The simulation of this test has been performing to verify the modal analysis of the developed model, and the modes shape result presented in figure 8 until figure 13. The results of modal analysis frequencies are present in fig 14.

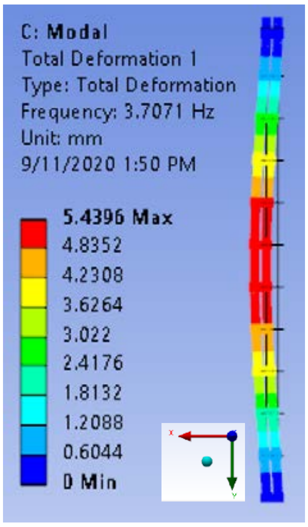

Fig 8. Mode-1

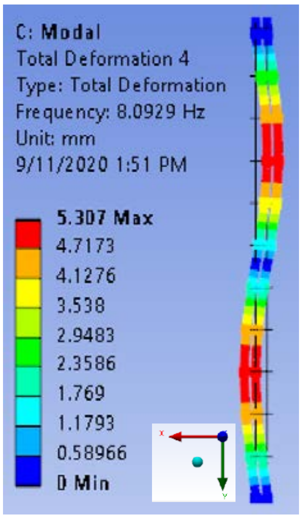

Fig 9. Mode-2

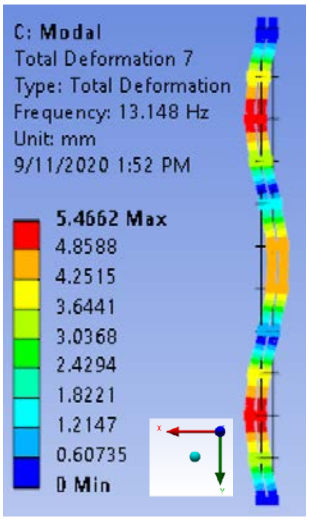

Fig 10. Mode-3

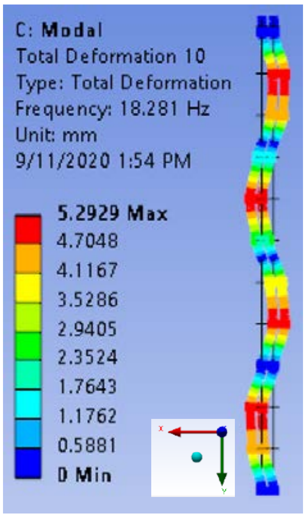

Fig 11. Mode-4

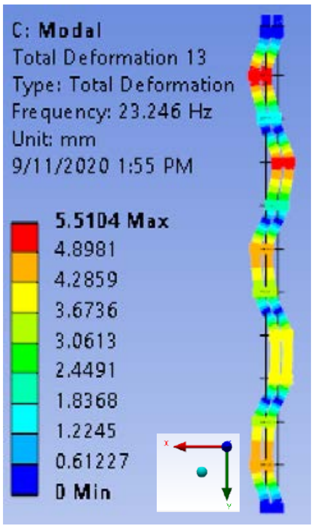

Fig 12. Mode-5

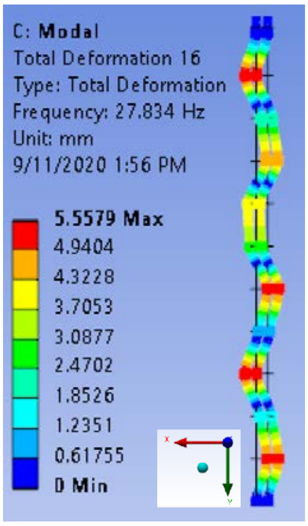

Fig 13. Mode-6

	Mode	Frequency [Hz]
1	1.	3.7071
2	2.	3.7118
3	3.	7.6614
4	4.	8.0929
5	5.	8.1062
6	6.	12.932
7	7.	13.148
8	8.	13.172
9	9.	17.095
10	10.	18.281
11	11.	18.317
12	12.	20.933
13	13.	23.246
14	14.	23.294
15	15.	24.573
16	16.	27.834
17	17.	27.893
18	18.	27.934
19	19.	30.872
20	20.	31.867

Fig 14. Result of 20 modes

Table 3. Comparison results

Mode	ANSYS Analysis *(Hz)*	Test*(Hz)* [10]	Error [%]
1	3.7071	3.7	-0.2
2	8.0929	8.1	0.1
3	13.148	12.91	-1.8
4	18.281	18.81	2.9
5	23.246	26.6	14.4
6	27.834	32.3	16.0

Based on the comparison of analysis results and test results, the analysis model can approximate quit well for frequencies below around 20 Hz range.

3 Conclusions and Future Considerations

Through the research, model reduction method were successfully applied to simplify FA dynamic analysis and following results are obtained.

- We created the shell model of lower end fitting and upper end fitting are compatible with the detailed 3D geometry.
- We also created much simpler beam model of spacer grid that produce similar modal frequencies of test result.
- We adjusted material properties of Young's modulus of spacer grid that produced similar dynamic behavior of modal value of test case.

With these valuable results, we can further reduce fuel assembly model that can be used to build 3D core model. Since core model involves 241 fuel assemblies, it is imperative to make fuel assembly model simple. This research is the first attempt to go in that direction.

4. Acknowledgement

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5. References

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