



## Vibration Analysis of a Dummy Fuel Rod Continuously Supported by Spacer Grids

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### ABSTRACT

The fuel rods in the pressurized water reactor are continuously supported by a spring system called a spacer grid (SG), which is one of the main structural components for the fuel rod cluster (fuel assembly). The fuel rods have a vibration behavior within the reactor due to coolant flow. Since the vibration, which is called flow-induced vibration, can wear away the surface of the fuel rod, it is important to understand its vibration characteristics. In this paper, a modal testing and a finite element (FE) analysis using ABAQUS on a dummy fuel rod continuously supported by Optimized H type (OHT) and New Doublet (ND) spacer grids are performed to obtain the vibration characteristics such as natural frequencies and mode shapes and to verify the FE model used. The results from the test and the FE analysis are compared according to modal assurance criteria values. The natural frequency differences between the two methods as well as the mode comparison results for the rod with OHT SG are better than those with ND SG. That is, in the case of the ND grid model using beam-spring elements, there was a large discrepancy between the two methods. Thus, we tried to modify the FE model for ND SG considering the contact phenomena between the fuel rod and the SG. The results of the new model showed good agreement with the experiment compared with those of a beam-spring model.

**KEY WORDS:** spacer grid, dummy fuel rod, natural frequency, mode shape, modal assurance criteria, flow induced vibration, Optimized H type, New Doublet, finite element analysis, contact model, ABAQUS, I-DEAS, PWR.

### INTRODUCTION

Pressurized water reactor (PWR) fuel rods, which are continuously supported by a spring system called a spacer grid, are exposed to reactor coolant at a flow velocity of up to 6-8 m/s. The coolant flow produces energy to induce vibrations in the fuel rods, which may result in structural damage. Since the coolant normally flows parallel to the fuel rods, the vibration is called an axial flow-induced-vibration (FIV). It is widely accepted that the primary excitation mechanism is the randomly fluctuating pressure acting on the surface of the fuel rods, and this constitutes the excitation force field [1]. The fuel rod extracts energy from the stochastic force field and vibrates predominantly in it. It is known that the vibration sources in the reactor exist in a wide range from 0 to 50 Hz [2]. It is important to understand how the fuel rods vibrate in the reactor because the sources can make a resonance with the fuel rod.

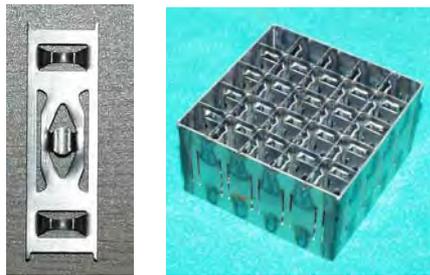
The SGs play an important role in supporting and protecting the fuel rod from external forces such as a seismic and a coolant flow, and must have strength enough so that an emergency cooling in the reactor may be possible. In order to verify the basic performance of the SGs in the design and development stages, the mechanical and structural tests such as an impact, a buckling, a fretting wear and supporting performance have been performed by authors [3-5]. From previous works for the vibrational behavior of the fuel rod with a SG, the vibration characteristics can be changed according to the design of the SGs which support the fuel rod, and those are reported by authors [6] for the fuel rod with the SG of several types. Thus, it is necessary to verify that the SGs are well designed without the separation between the fuel rod and the SG under normal operating conditions. It is obvious the best way to verify the supporting performance of the SGs is the vibration test in the reactor in-core performed under normal operating conditions. But is it actually impossible, because there are many difficult and dangerous things owing to the characteristics of nuclear facilities. Therefore the theoretical and numerical approaches based on actual models are generally used. Among these methods, a useful approach is the FE analysis using a commercial code. In this case the reliability and the verification of the model developed is very important. Kang et al. [7,8] have studied the vibration behavior of the fuel rod with the SG using an experimental method and performed the updating of the FE model using the measured data in order to enhance confidence in the FE model of fuel rod supported by SGs.

The vibration characteristics of the fuel rod 2.19 m in length supported by 5 SGs are investigated for two different types of OHT and ND SGs by modal testing and FE methods using ABAQUS [9]. The FE analysis models are generated using an I-DEAS program [10] and the results are compared with those of the test to verify the FE model. From the comparison of two results for the fuel rod with ND SG, in case of the ND SG model using beam-spring elements, there are large differences between the two methods with lower values in the FE results. These discrepancies can be reduced by the modification of the FE model considering the contact phenomenon between the fuel rod and the SG.

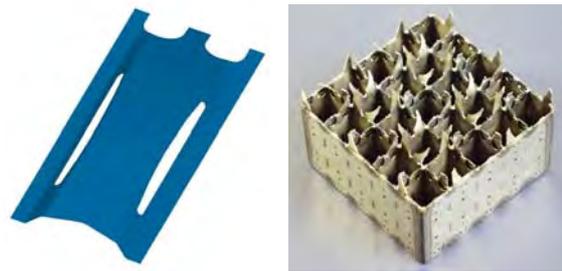
## EXPERIMENTAL MODAL TESTING

### Test Specimens

Figs. 1 and 2 present the unit cell and 5×5 partial grid of the OHT and ND SGs, respectively. The ND SG has good wear and tear characteristics at the contact parts between the rod and the SG, and the stiffness of a SG can be controlled by the existence of the slot, which is slender and long at both sides of the spring. Fig. 3 shows the schematic view of a fuel rod model, which can be considered as the beam continuously supported by several OHT SGs. In general, there are two springs and four dimples whose stiffness is much larger than that of the two springs, within a single cell of a SG as shown in Fig. 1. The geometrical shape and dimensions of the dummy fuel rod used in the experimental modal testing are shown in Fig. 4. The dummy fuel rod consists of two parts; the stack region with Pb pellets and the plenum region with a spring and a space filled with helium gas. The fuel rod is a cylindrical tube 9.5 mm in external diameter, 0.64 mm in thickness and 2.19 m in length. In the stack region the Pb pellets with a density of 10.4 g/cm<sup>3</sup> are used instead of UO<sub>2</sub> pellets with a density of 11.4 g/cm<sup>3</sup>. All components of the dummy fuel rod such as the end cap, cladding and the plenum spring are the same as those of the actual fuel rod except for the pellets.



(a) Unit cell (b) 5x5 partial grid  
Fig. 1 OHT spacer grid



(a) Unit cell (b) 5x5 partial grid  
Fig. 2 ND spacer grid

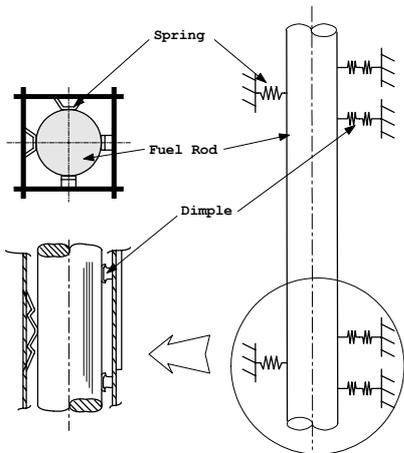


Fig. 3 Schematic view of the fuel rod supported by SG

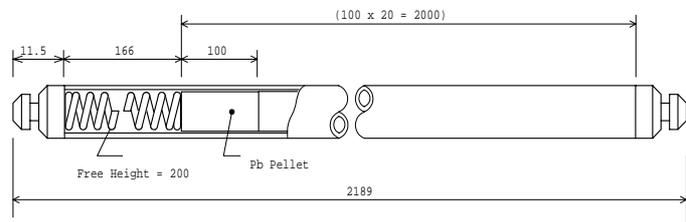


Fig. 4 Dimensions of the dummy fuel rod (unit: mm)

### Test Overview

The experimental modal testing to obtain the natural frequencies and mode shapes of the dummy fuel rod in air and under water are performed and used to test the apparatus and sensors such as the data acquisition & control system (Agilent VXI HP7500), a shaker (WILCOXON), an accelerometer (RION PV-90B), a laser vibrometer (Polytec) and I-DEAS TDAS software etc.. The shaker is installed at the three-quarters position of the second span, and works by a trigger input signal from the VXI front end. Accelerometers are attached at the one-quarters and three-quarters for each span of the fuel rod, and the center position of the second span as shown in Fig. 5. It has one additional accelerometer and a laser displacement sensor which are installed in order to obtain the displacement of the span where the shaker works. The modal testing is performed by sine sweep using the closed loop control in the frequency range of 5~150 Hz in air and under water conditions. The I-DEAS TDAS software is used for the data acquisition, the modal analysis and the correlation of results between the test and the FE analysis.

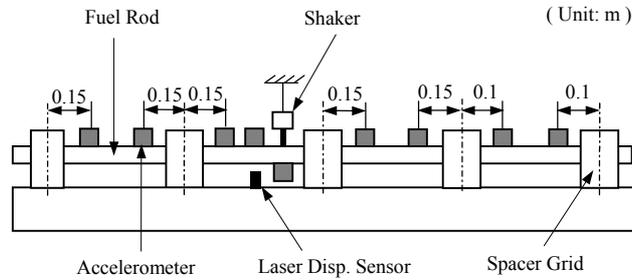


Fig. 5 Installation position of various sensors

## FINITE ELEMENT ANALYSIS

### Analysis Model and Approach

To compare and verify the test results the free vibration analysis using a commercial FEA code, ABAQUS is conducted. For the numerical modal analysis, a planar beam element (B21) that uses linear interpolation is used for the fuel rod, and a spring element (SPRINGA) for the spring and dimple of the SG. The Lanczos method is used to extract eigenvalues and eigenvectors of the fuel rod. The linear characteristics of the spring and dimple in N/mm unit are obtained by bending tests using a universal test machine [11], and spring constants used in the FE analysis are as below;

- Optimized H type: Spring constant= 128 N/mm, Dimple's spring constant= 506 N/mm
- New Doublet: Spring constant= 114 N/mm

Generally, the dimple can be considered as showing the rigid body motion because the stiffness is a greatly higher value than that of the spring. The damping and the effect of the friction between the rod and the SG in the FE analysis are ignored. To consider the water effect in the FE model, a volume of the fuel rod is calculated and used as the added masses in the room temperature, and the total densities including the masses of the water and Pb pellet are considered as  $10,600 \text{ kg/m}^3$  for the plenum region and  $11,193 \text{ kg/m}^3$  for the stack one.

## RESULTS AND DISCUSSION

### Displacements

In general, it is known that the fuel rod has less amplitude than 0.2 mm under normal operating conditions of the reactor. Thus if we obtain the displacement of the fuel rod with an excitation force, we can predict the natural frequencies in case of the experiment to those of the real operating conditions in the reactor. To determine the force showing about 0.2 mm displacement, the displacement with the excitation forces are measured using a laser Doppler vibrometer at the center of the second span to predict the maximum displacement occurring due to the excitation of the shaker.

Table 1 presents the measured displacement for the dummy fuel rod supported by OHT and ND SGs in air and under water conditions. The displacement histories of the frequency domain with the force level of the rod supported by OHT SG in air are shown in Fig. 6. For the same excitation force, in case of the fuel rod supported by OHT SG, the displacements are larger than those of the ND one. The natural frequencies decrease with increasing force levels. Those trends in the results were first reported by Premount [11], and is the typical behavior of structures having nonlinear characteristics. It is believed that the fuel rod has nonlinear softening characteristics on the force level. In case of the OHT SG under water, the displacements with the force levels have the same or slightly lower values than those in air. But for the ND SG the displacement under water has higher ones than in air.

Table 1 Measured displacements of the fuel rod supported by OHT and ND SGs

Grid	Optimized H type				New Doublet			
	In air		Under water		In air		Under water	
Force	Disp.	Freq.	Disp.	Freq.	Disp.	Freq.	Disp.	Freq.
0.25 N	0.10	34.64	0.10	32.21	-	-	-	-
0.50 N	0.22	32.44	0.21	31.02	0.10	48.57	0.12	45.32
0.75 N	0.29	31.47	0.28	30.05	0.13	47.04	0.21	44.35
1.00 N	-	-	-	-	0.19	47.03	0.23	44.04
1.25 N	-	-	-	-	0.20	45.75	0.25	43.74

If the same energy inputs are used for the same structure, but different natural frequencies exist due to different environments, it is obvious that we could get a bigger displacement when we have a lower natural frequency. This trend has been represented by author's previous works [7] for the fuel rod supported by other type of SGs. As a result, the

excitation force showing the similar result with a maximum displacement on the steady-state operating condition of the reactor under water is 0.5 N for the OHT SG and 0.75 N for the ND one, and in case of both the displacements measured it is 0.21 mm.

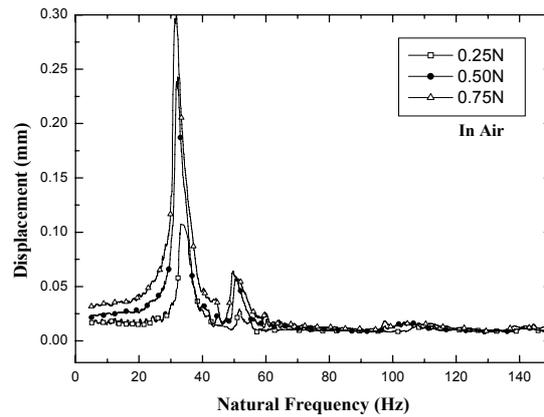


Fig. 6 Measured displacement of the fuel rod supported by OHT SG

### Natural Frequencies and Mode Shapes

The comparison of natural frequencies and MAC values for the dummy fuel rod supported by OHT and ND SGs under 0.5 N and 0.75 N in air are listed in Table 2. Here, the error presents the percentage difference between the experiment and FE analysis results, and the result of FE analysis does not show the variation with the force because the free vibration analysis is conducted. The experimental natural frequencies are lower than those of the FE analysis, and in case of the excitation force level, 0.5 N the fundamental frequency shows 32.44 Hz for the experiment and 40.06 Hz for the FE analysis. The discrepancy of the two methods is about 13 % as an average value. The reason why the test results are lower than that of FE analysis is that the fuel rod with OHT SG in the experiment can have contact or separation between the fuel rod and the spring/dimple of the SG, and this phenomenon can play an important role in the decrease of the natural frequency. One of the other reasons for the discrepancy is that the FE analysis has generally an upper bounded value. For the fuel rod with ND SG, there is about 30 % deviation for the fundamental frequency showing higher test values than those of the FE analysis. These results are contrary to the FEA results of the OHT SG that are showing higher values than the test results. It is believed that there are discrepancies between the two methods because the ND SG is modeled with beam-spring elements and doesn't consider the contact area between the rod and the SG. Therefore, we developed a FE model considering the contact phenomenon between the fuel rod and the SG in order to reduce the difference. The analysis methods and results for the new FE model will be presented in the following section in detail.

Table 2 Natural frequencies and MACs of the fuel rod supported by OHT and ND SG with force levels in air

Force (N)	Mode	Optimized H type				New Doublet			
		Test	FEA	Error*(%)	MAC	Test	FEA	Error*(%)	MAC
0.5	1	32.44	40.06	-23.5	0.951	48.57	32.23	33.6	0.980
	2	46.31	46.62	0.67	0.879	49.90	39.86	20.1	0.365
	3	49.44	55.64	-12.5	0.923	53.53	50.32	6.01	0.924
	4	98.63	85.55	13.3	0.279	-	70.40	-	-
	5	108.4	126.9	-17.2	0.837	128.45	114.89	10.6	0.801
0.75	1	31.47	40.06	-27.3	0.935	47.04	32.23	31.5	0.950
	2	44.88	46.62	-3.9	0.945	49.25	39.86	19.1	0.130
	3	49.07	55.64	-13.4	0.932	51.06	50.32	1.45	0.940
	4	101.4	85.55	15.6	0.505	-	70.40	-	-
	5	105.9	126.9	-19.8	0.888	128.18	114.89	10.4	0.814

\*  $Error = (Test - FEA) / Test \times 100(\%)$

Fig. 7 shows the comparison of the natural frequency with force levels for the fuel rod with OHT SG in air and under water. As expected, the natural frequencies of the fuel rod under water decrease due to the so-called added mass effects. The natural frequencies both in air and under water decrease as the excitation force increases, and those under water decrease about 4.4 % for the force level, 0.5 N. Also the decrease of the frequency with force levels is larger in air than under water. This means the excitation force has a more sensitive effect on the natural frequencies in air than

under water condition.

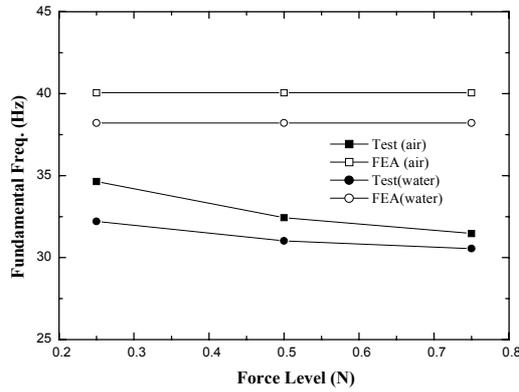


Fig. 7 Fundamental frequencies of the fuel rod supported by OHT SG with force levels

Figs. 8 and 9 show the typical MAC result and a comparison of mode shapes for the fuel rod with OHT SG under the force level, 0.25N in air. Generally, in order to compare and estimate the difference in dynamic characteristics between the experimental and FE model, mode pairing was done by the well-known modal assurance criterion (MAC). Since the MACs represent the directional cosine between the two modes, and if the experimental and FEA mode shapes are the same mode, the MAC value close to 1.0 is expected, whereas if they actually relate to two different modes, a value close to 0 (zero) should be obtained. It is found that a value in excess of 0.9 should be attained for correlated modes and a value of less than 0.05 for an uncorrelated model [12]. As shown in Table 2 and Fig. 8, the MAC values are very similar for the first three modes. But for the higher modes, especially at the 4<sup>th</sup> mode, the value is relatively small compared with the lower ones, and becomes smaller as the force level increases. The reason for the lower MAC values at the high frequencies can be explained by a comparison of mode shapes between the two methods as shown in Fig. 9. The open circle lines are the mode shapes obtained by experimental modal testing, and the solid ones by FE analysis. It can be found that the mode shapes between the two approaches are in good agreement when the MAC values close to 1.0 are obtained. The 4<sup>th</sup> mode shape of the FE analysis is the predominant motion at the 4<sup>th</sup> span, but in the experiment the behavior of the 2<sup>nd</sup> and 3<sup>rd</sup> spans is relatively large. Those results are because the shaker attached at the 2<sup>nd</sup> span plays a role in the distortion of the 4<sup>th</sup> mode, and increases as the force level increases.

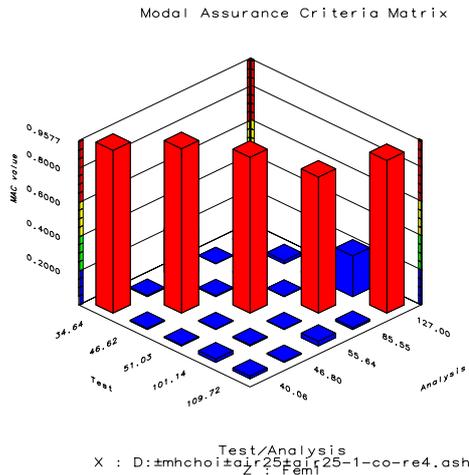


Fig. 8 MACs of the fuel rod supported by OHT SG under 0.25 N in air

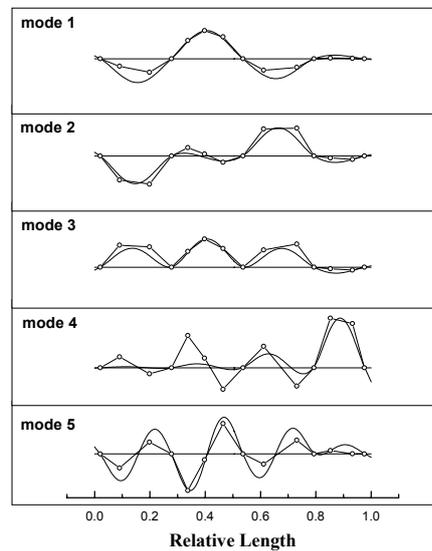


Fig. 9 Mode shape comparison of the fuel rod supported by OHT SG under 0.25 N in air

**New Model for the Fuel Rod with ND SG**

As mentioned above, the new FE model tried to reduce the differences between the experimental and numerical results in case of the fuel rod with ND SG, and by considering the contact phenomena between the fuel rod and the SG. Fig. 10 presents the detailed contact parts of the new FE model. The 4-node, quadrilateral, stress/displacement shell element (S4R) is used to generate geometrical shapes for the fuel rod and the SG. In the new FE model only the top and bottom cells of the SG are considered in the supporting parts because we are interested in the behaviors in the normal direction (2 in the FE model coordinate). When the fuel rod is inserted in the SG assembly, the SG may be deformed by 0.15mm for one side in the normal direction, and it is considered as the initial contact distance as shown in Fig 10(b).

As boundary conditions, since both edges of the unit cells are welded with each other, fixed conditions at both edges along the axial direction (3) are applied. The displacement of the rod in the width direction (1) is also constrained to obtain the motions in the normal direction only. The analysis to calculate modal characteristics for the new model is performed by solving the following two steps; contact and modal analysis. First, the small sliding contact problems between the two contact surfaces are defined as MASTER for the fuel rod and SLAVE for the SG, are solved. Next, the modal analysis using the Lanczos method is performed.

Table 3 presents the comparison of natural frequencies and MAC values for the new model considering the contact between the fuel rod and the ND SG. As discussed in Table 2 previously, when the beam-spring element is used in the FE analysis, the fundamental frequency is 32.23 Hz. But that of the new contact model is 48.01 Hz, and it's increased by about 32 % from that of the previous simple model. When the results are compared with the experimental ones, the natural frequencies after the model change are also in good agreement within 3 % error, except the 3<sup>rd</sup> mode with 7.2 % one.

Table 3 Comparison of natural frequencies and MAC values for the fuel rod with ND SG using new FE model

Mode	Test	Beam-Spring Model	MAC	Error* (%)	Contact Model	MAC	Error* (%)
1 <sup>st</sup>	47.04	32.23	0.950	31.5	48.01	0.932	-2.1
2 <sup>nd</sup>	49.25	39.86	0.130	19.1	50.72	0.034	-3.0
3 <sup>rd</sup>	51.06	50.32	0.940	1.45	54.77	0.956	-7.2
4 <sup>th</sup>	-	70.40	-	-	99.30	-	-
5 <sup>th</sup>	128.2	114.9	0.814	10.4	132.0	0.471	-3.0

\*  $Error = (Test - FEA) / Test \times 100(\%)$

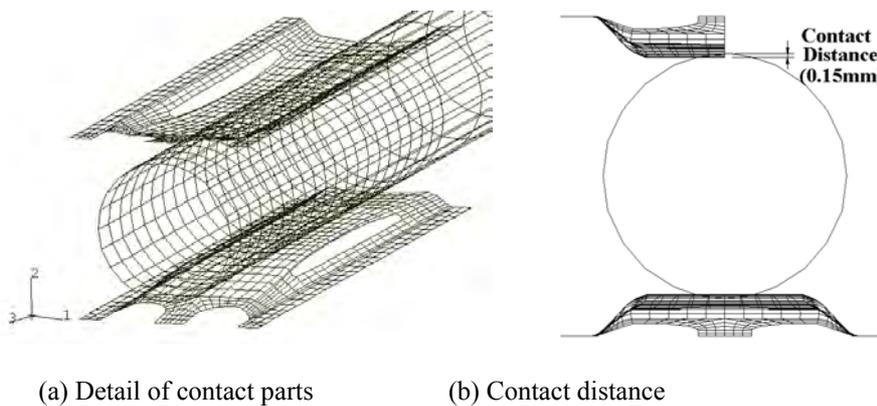


Fig. 10 New finite element contact model

Figs. 11 and 12 show the MAC graph and mode shapes of the fuel rod supported by ND SG considering the contact, respectively. Similar to the results of previous model using beam-spring elements, the MAC value at the 2<sup>nd</sup> mode is very poor because there is quite a large difference in the modes between the test and the FE analysis at the 2<sup>nd</sup> span. But the natural frequencies of the new model show good agreement with the experimental results compared with those of previous simple models. As a result, for the fuel rod supported by ND SG with area contacts, it is found that the natural frequencies can be more exactly calculated by the new FE model considering the contact phenomenon, although tedious work for the FE modeling and long runtimes for a computation are necessary. It is also expected that the new model developed can be applied to predict the vibrational behavior of the fuel rod without experimental modal testing, when the geometrical shape such as the length between the two SGs or the number of the SGs are changed.

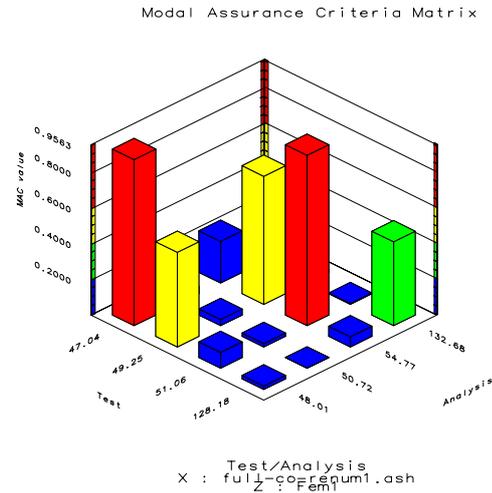


Fig. 11 MAC values between the experimental and new FE model results

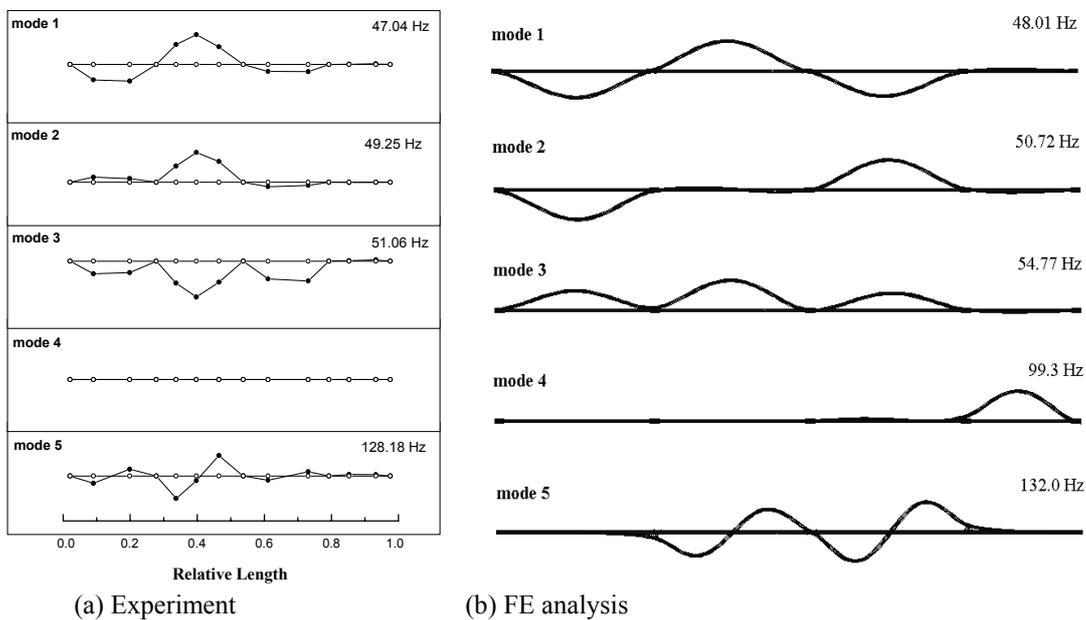


Fig. 12 Mode shapes of the fuel rod with ND SG by test and FE analysis

## CONCLUSION

- (1) The excitation force showing the displacement of about 0.2 mm in the experiment is 0.5 N for the OHT SG and 0.75 N for the ND SGs, respectively. In this case, the experimental natural frequencies of the fuel rod in air is 32.44 Hz for the OHT SGs and 47.04 Hz for the ND ones, and the frequency of the fuel rod with ND SG is higher by 15 Hz than that of the case of the rod with OHT SGs. For both SGs, natural frequencies under water decrease by about 5 % due to the added mass effects of the fluid.
- (2) According to the increment of the excitation force levels, the displacements of the fuel rod increase and the natural frequencies decrease. It is believed that the fuel rod has nonlinear softening characteristics because those trends are the typical behavior of structures having a non-linearity.
- (3) The experimental mode shapes have relatively large differences with those of the FE analysis at the 2<sup>nd</sup> and 4<sup>th</sup> frequencies showing the 2<sup>nd</sup> bending mode. Especially, for the fuel rod with ND SGs the discrepancy of the mode for the 2<sup>nd</sup> span is large, and the 4<sup>th</sup> mode in the experiment can't be obtained. It is believed that the excitation force distorts the experimental mode of the 2<sup>nd</sup> span showing the 2<sup>nd</sup> bending mode.
- (4) A comparison of mode shapes and MACs between experimental and FEA results show that the results are good and the FE model can be reliable for the fuel rod with OHT SG. However, for the fuel rod with ND SG, there are some discrepancies between the two results. Actually, when the beam-spring simple model is used, the difference

of the frequencies between the two methods are about 30% but the use of the new FE model considering the contact phenomenon can decrease the differences to a maximum error of about 7.2%.

- (5) It is expected that the new FE model can be applied to predict the vibrational behavior of the fuel rod with ND SG without an experiment, and respond to many design changes quickly.

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