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Verification Test and Model Updating for a Nuclear Fuel Rod with Its Supporting Structure

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Abstract

Pressurized water reactor(PWR) fuel rods, which are continuously supported by a spring system called a spacer grid(SG), are exposed to reactor coolant at a flow velocity of up to 6~8 m/s. It is known that the vibration of a fuel rod is generated by the coolant flow, a so-called flow-induced-vibration(FIV), and the relative motion induced by the FIV between the fuel rod and the SG can wear away the surface of the fuel rod, which occasionally leads to its fretting failure. It is, therefore, important to understand the vibration characteristics of the fuel rod and reflect that in its design. In this paper, vibration analyses of the fuel rod with two different SGs were performed using both analytical and experimental methods. Updating of the finite element(FE) model using the measured data was performed in order to enhance confidence in the FE model of fuel rods supported by an SG. It was found that the modal parameters are very sensitive to the spring constant of the SG.

Key Words : fuel rod, vibration, modal test, natural frequency, MAC, model updating, spacer grid

1. Introduction

A PWR fuel rod(FR) continuously supported by several SGs as shown in Fig. 1, is exposed to reactor coolant at a flow velocity of up to 7 m/s. The coolant flow produces energy to induce vibrations in the FRs, which may result in structural damage. Since the coolant normally flows parallel to the rods, the vibration is called an axial-flow-induced vibration. It is widely accepted that the primary excitation mechanism is the randomly fluctuating pressure acting on the surface of the rods, and this constitutes the excitation force field[1]. The FR extracts energy from the stochastic force field and vibrates predominantly in its few lower modes. The relative motion between the FR and SG induced by the FIV is the root cause of the fretting wear damage of the FR.

The inside of the FR is pressurized by helium gas, up to 26 bars to prevent it from being crushed by the high coolant pressure of 150 bars in the reactor. The internal pressure of the FR in the reactor increases due to fission gases released

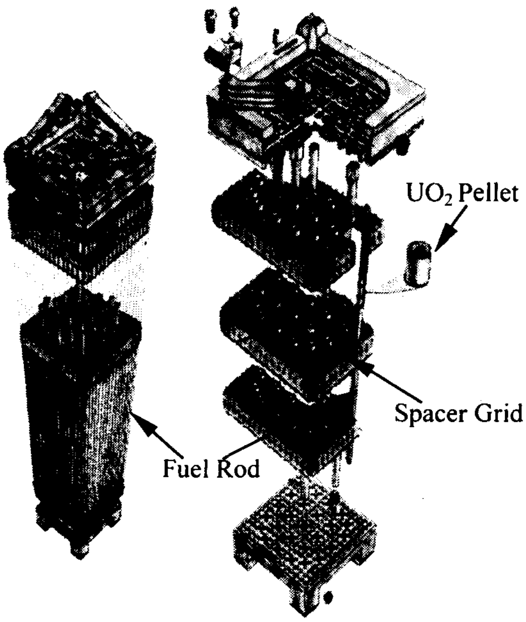


Fig. 1. Fuel Rods in PWR Fuel Assembly

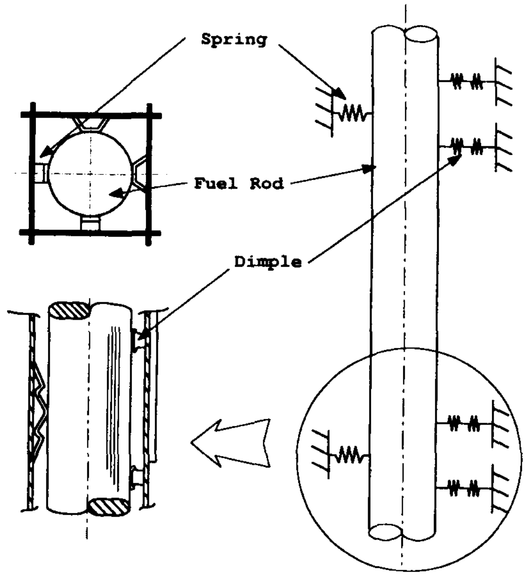


Fig. 2. Fuel Rod Model with Spacer Grids

from the UO_2 pellets in it as burnup increases. Therefore, the FRs are subjected to tension in the air and to compression after being loaded into the reactor, which gradually decreases as burnup increases.

Since the slenderness ratio(L/D) of the FR is so big, it is generally considered as the Euler-Bernoulli(E-B) beam continuously supported by several SG and subjected to an axial force. Generally speaking, there are two springs and four dimples whose stiffnesses are much larger than those of the two springs, within a single cell of the SG as shown in Fig. 2.

It is known that the number of SG per fuel assembly(FA) and the spring constants have a significant effect on the modal parameters of the FR. An increment in the number of SG is good from the viewpoint of the decrease of the vibration amplitude of the FR because it makes the span length(length between SGs) short, and the boundary condition of the FR stiff. However, this is restricted due to negative effects on thermal/hydraulic parameters like pressure drop and heat transmission. Therefore, the spring constant is the only parameter that is controlled in the development and design of the SG. Strictly speaking, however, even the establishment of the spring constant is limited within some range from the viewpoint of radiation effects.

In this paper, modal analyses of the FR supported by 5(five) SGs was performed for two different SGs in numerical and experimental ways. Updating of the finite element(FE) model using the measured data was performed in order to enhance confidence in the FE model of fuel rods supported with an SG.

2. Experiment

The number and position of the accelerometers were determined by the optimal experiment design method which was done using a commercial package (FEMtools)[3]. The optimal measurement points determined are shown in Fig. 3

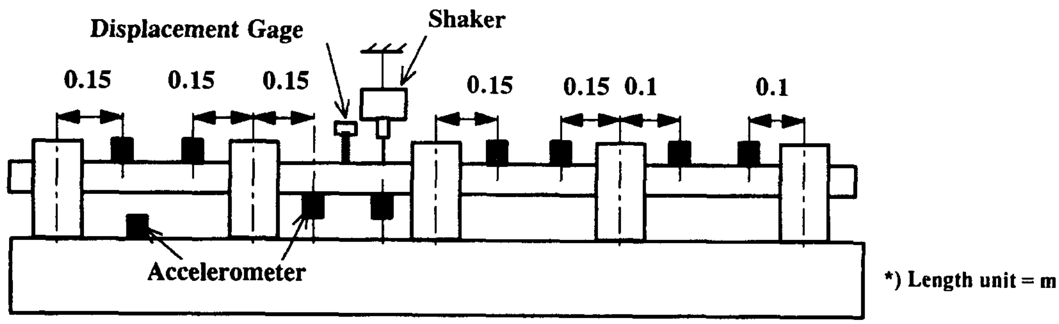


Fig. 3. Modal Test Setup for FR with Spacer Grids

Pb pellets were inserted instead of UO_2 pellets in the test FR. The impact shaker worked by a trigger input signal. I-STAR was used for data acquisition, and modal analysis was finally performed with FEMtools. Two accelerometers were attached at the one-fourth and three-fourths of a single span of a fuel rod. In addition, one accelerometer was attached on the bed to monitor noise isolation. Therefore, nine accelerometers were used as shown in Fig. 3. Also, a laser displacement gage was installed in order to check the displacement of the span where the shaker worked.

Since the vibration amplitude of the FR in PWR reactor was known to be less than 0.2 mm, 0.5, 1 and 2 N input forces were employed in consideration of that amplitude. The vibration test was performed in air, under cold water and 80℃ hot water

3. Analysis

3.1. Finite Element Analysis

For the numerical analysis, a 2-D beam element of ANSYS[2] was used. The frequency range to be calculated was set as 0 to 100 Hz, and modes from 0 to 4. The spring and dimple of the SG were simulated as bent springs. Both spring and dimple constants were obtained by actual tests[6] as shown in Table 1.

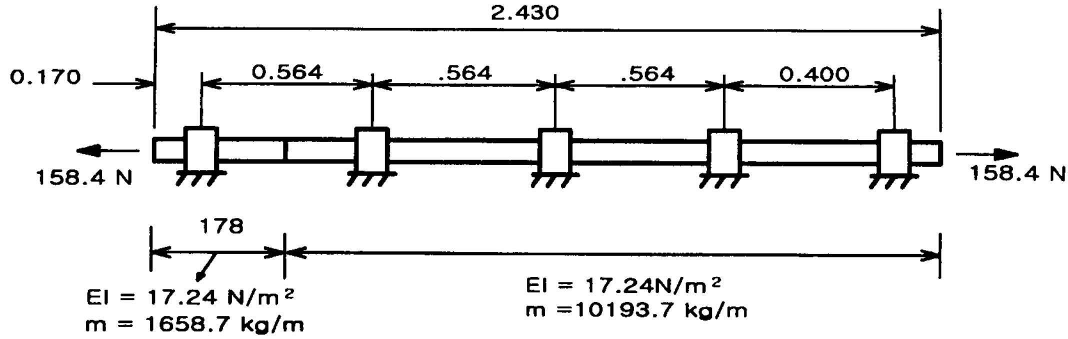
Table 1. Spring and Dimple Constants for the Spacer Grid Type A B

Spring/dimple \ Grid Type	A	B
Spring(N/mm)	152.9	361.8
Dimple(N/mm)	8840	7700

The model geometry and material properties for FE analysis (FEA) are shown in Fig 4. For the calculation of Young's modulus(E) and the moment of inertia(I) of the rod, the contribution of the Pb pellets was disregarded, as other researchers have done. Water density, material properties and spring constants at the temperature we wanted were used for the calculation of the results shown in Table 2. It was assumed that the spring constant would be changed at the same rate

Table 2. Natural Frequencies Calculated by FEM for a FR Supported by Both Spacer Grid A and B

Mode \ Grid Type	A	B
1(Hz)	43.9	42.9
2(Hz)	48.3	47.6
3(Hz)	53.8	53.5
4(Hz)	86.8	86.2



***) Length unit = m**

Fig. 4. Geometry and Material Properties for the FR Model

as Young' s modulus was changed due to temperature variation.

3.2. Model Comparison

Since the FR has a uniform mass per length, and its dimensions are strictly controlled during manufacturing, structural modification on the mass or stiffness term is meaningless. It is known that the dynamic behavior of the FR is significantly influenced by the characteristics of the SG spring and dimple. For this reason, sensitivity studies and modification were performed regarding the spring and dimple constants. An accurate FE model of the FR requires accurate simulation of the spring boundary conditions.

In order to find out and modify the differences in dynamic characteristics between the experimental and FE model, mode pairing was done by the well-known Modal Assurance Criteria(MAC) equation as follows:

$$MAC(\Psi_F,\Psi_E)=\frac{\left|\left(\{\Psi_F\}^T\{\Psi_E\}\right)\right|^2}{\left(\{\Psi_F\}^T\{\Psi_F\}\right)\left(\{\Psi_E\}^T\{\Psi_E\}\right)} \quad (1)$$

Where, Ψ_F and Ψ_E is the mode shape obtained by FE and experiment model respectively. Superscript T means transposed.

3.3. Sensitivity Analysis

In the case of the type A SGs, the difference in the 1st natural frequency between FEA and EMA was large. Sensitivity analysis on the SG spring and dimple was performed with the following equations for the A type SG prior to updating of the FE model

$$\frac{\partial\{\Psi_i\}}{\partial p}=\sum_{k=1}^{N}a_k^i\{\Psi_k\} \quad (2)$$

$$a_k^i=\frac{\{\Psi_i\}^T\left(\frac{\partial[K]}{\partial p}-\lambda_i\frac{\partial[M]}{\partial p}\right)\{\Psi_i\}}{\lambda_i-\lambda_k} \quad \text{if } k\neq i \quad (3)$$

where, p : parameter selected for sensitivity analysis
$[K]$: stiffness matrix
$[M]$: mass matrix
λ : eigenvalue

3.4. Model Updating

Model updating is a process for improving an FE model of a structure using measured dynamic data from the same structure. Over the past decade or so a number of updating techniques have been proposed. A review of the different methods can be found in reference 4. In this study, the Bayesian parameter estimation method is used, which includes the use of weighting coefficients on the parameters as well as on the responses. The discrepancy between the initial model predictions and the test data is resolved by minimizing a weighted error defined as follows:

$$\Omega = [\{R_e\} - \{R_a\}]^T [C_R][\{R_e\} - \{R_a\}] + [\{P_u\} - \{P_o\}]^T [C_P][\{P_u\} - \{P_o\}] \quad (4)$$

Where, R : Structural Response
(a: analysis, e: experiment)
P : Parameter
(u: updated, o: original)
C : Weight Function
(R: response, P: parameter)

Updating a parameter is performed by using the equation (5).

$$\{P_u\} = \{P_o\} + [G][\{R_e\} - \{R_a\}] \quad (5)$$

In equation (5), [G] is a gain matrix as follows:.

$$[G] = \left(2[C_p] + [S]^T [C_R][S]\right)^{-1} [S]^T [C_R] \quad (6)$$

where, [S] is a sensitivity matrix defined as the following equation (7)

$$[S] = S_{ij} = \left[\frac{\delta R_i}{\delta P_j}\right] \quad (7)$$

The same weighting was imposed for physical quantities(C_p) such as mass and stiffness of the FR, however, a higher weighting was put on the lower modes since the lower mode was known to have a higher contribution to the vibration.

4. Results and Discussion

The natural frequencies with the force level obtained by the tests are summarized in Table 3. It was observed that the natural frequencies were apt to decrease with an increase of the force level. It is believed that the FR has nonlinear characteristics on the force level, which was first reported by Premount[5]. This phenomenon is believed to be due to the nonlinear characteristics of the spring. This could be assumed as a linearity if the analyses were carefully controlled by the input force level. As expected, the natural frequencies of the FR under cold water decrease due to the so-called added mass effect. However, in hot water (80 ℃), the natural frequencies increased more than our expectation that the added mass effect would decrease due to the decrease of water density. This could be explained by the increase of the internal pressure caused by the isovolumetric change of helium gas as the temperature increased. The pressure increased the axial force on the FR, which made the stiffness term strong, and the natural frequencies increased. A bigger displacement of the FR under cold water than in air was observed at the same force level. If the same energy inputs were used for the same structure, but different natural frequencies existed due to different environments, it was obvious that we could get a bigger displacement when we have the lower natural frequency. The displacement of the FR under hot water could not be measured due to vapor, which disturbed the operation of the laser displacement gage. Two typical FRFs for the three different environments are shown in Figs. 5 and 6. As mentioned before, nonlinear characteristics are observed.

The natural frequencies for the FR with type A SGs are much lower than those with type B SGs at same force level. These results are contrary to

Table 3. Natural Frequency and Displacement Comparison According to Force (in-air)

Force Level	Mode \ Type	In-air A	In-air B	Cold Water A	Cold Water B	Hot Water(80℃) A	Hot Water(80℃) B
0.5 N	1st mode (Hz)	35.2	44.4	33.7	42.5	33.9	44.7
	Disp. (mm)	0.05	0.016	0.07	0.019	-	-
1.0 N	1st mode (Hz)	33.6	40.6	31.5	40.2	32.4	42.5
	Disp. (mm)	0.098	0.040	0.113	0.053	-	-
2.0 N	1st mode (Hz)	30.7	37.4	28.8	37.5	29.5	39.8
	Disp. (mm)	0.196	0.106	0.229	0.134	-	-

Table 4. Comparison with FE Analysis and Experimental Results for A Type SG

Mode	A TYPE				B TYPE			
	FEA	EXP	Error (%)	MAC (%)	FEA	EMA	Error(%)	MAC(%)
1	43.9	35.2	24.69	83.2	42.9	44.4	-3.24	88.8
2	48.3	46.4	4.14	55.4	47.6	50.5	-5.82	59.5
3	53.8	49.2	9.45	94.8	53.5	52.3	2.35	92.6

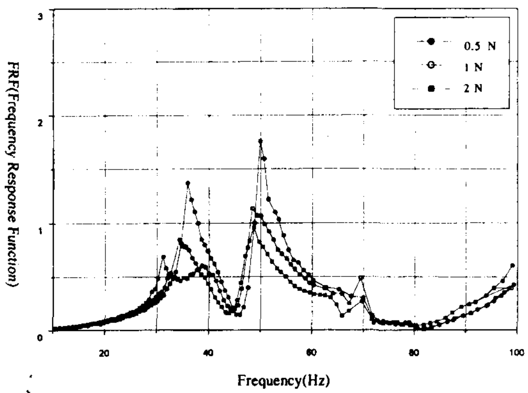
the FEA prediction that the natural frequencies for type B SGs are slightly lower than those for type A SGs. For this reason, it is necessary to compare both models, to analyze sensitivity of a parameter, and to perform model updating with it.

A comparison of the results of experiment (EMA) with FEA on the FR with both type A and B SGs are shown in Table 4. The MAC analysis result for the A type SG is representatively depicted in Fig. 7. Modal Assurance Criteria(MAC) is used for the comparison between the numerical and experimental models. Since the MAC represents the directional cosine between two vectors, 0(zero) means that two vectors never have any similarity, and one(100%) means that two vectors are identical. The MACs for both SGs are very similar. The values from odd(first and third) modes are relatively high as compared with even (second) modes.

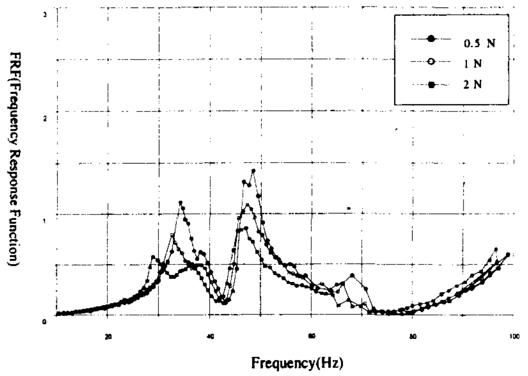
Three(3) modes have been identified by the experiment. The discrepancy of the 1st natural frequency is large between FEA and EMA with the A type SG, while relatively good agreement was obtained with the B type SG.

Each mode shape for the FR with both SG shows the same pattern as shown in Fig.8. The black lines are the mode shapes obtained by FEA, and the red ones by EMA. The red solid circles represent the positions of accelerometers.

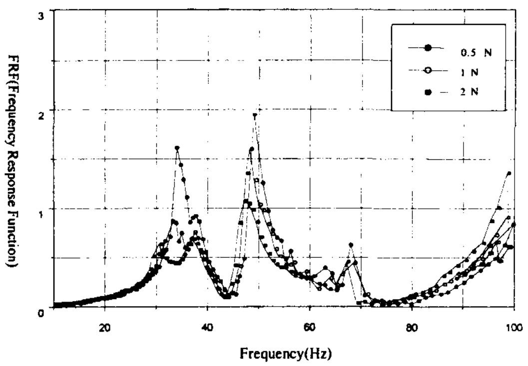
It is impossible for such a large difference between FEA and EMA to be due to mass or stiffness inconsistency, but possible for it to be due to the stiffness discrepancy of the SG spring or dimple. The sensitivity analysis results according to the mode shapes are shown in Fig. 9 for the A type SG. Five springs were represented as parameters 1 through 5, and ten(10) dimples as 6 through 15. The stiffness of the dimple in the SG was more sensitive to the dynamic characteristics of the FR than those of the spring.



a) In Air

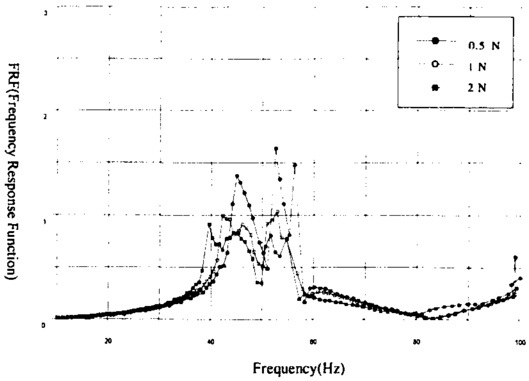


b) Under Cold Water

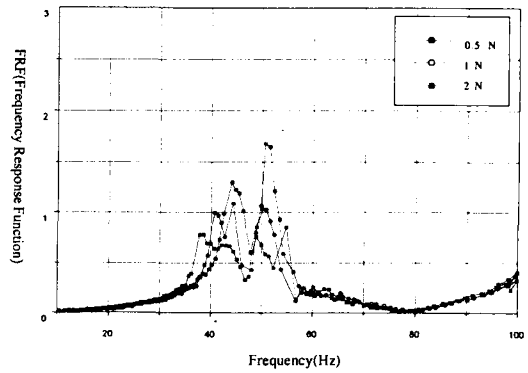


c) Under Hot Water (80 °C)

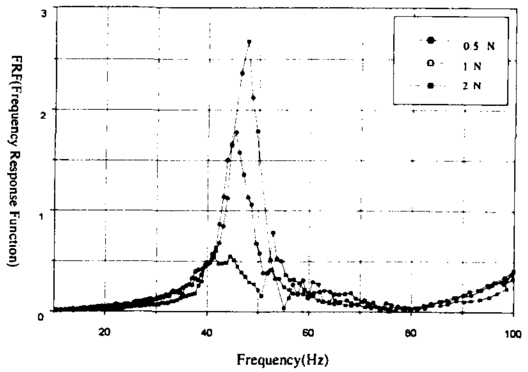
Fig. 5. FRFs for the FR with SG Type A



a) In Air



b) Under Cold Water



c) Under Hot Water (80 °C)

Fig. 6. FRFs for the FR with SG Type B

Updating of the FE model of the FR with an A type SG using the measured data was performed to enhance confidence in the FE model. The Bayesian parameter estimation

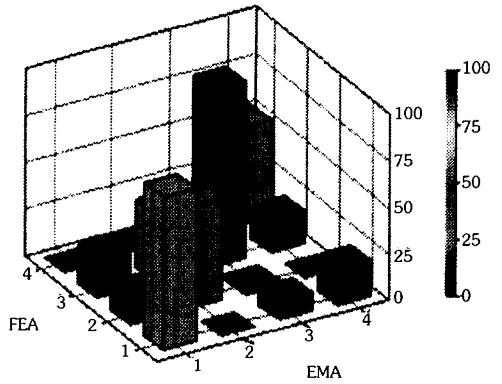


Fig. 7. MAC Comparison for A Type SG

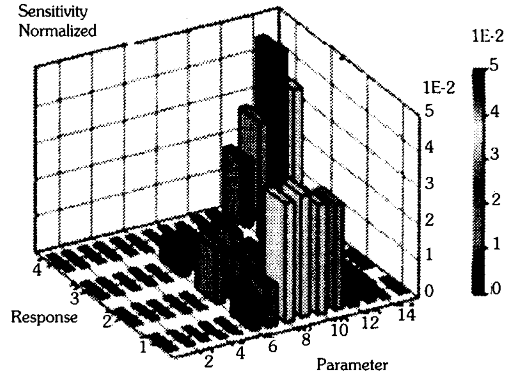


Fig. 9. Sensitivity Comparison for Spring and Dimple Stiffness of A Type SG

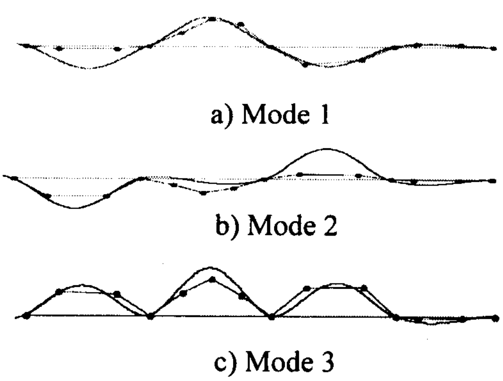


Fig. 8. Mode Shapes of FR with A Type SG (Before Updating)

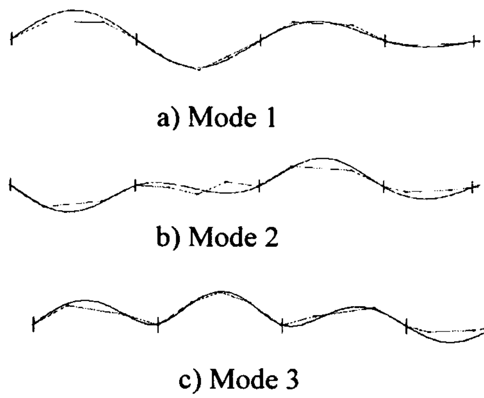


Fig. 10. Mode Shapes of FR with A Type SG (After Updating)

formula was utilized for the model updating. Since the fuel rod has well-controlled mass per length and stiffness, sensitivity analysis and model updating were performed on the support spring constant. The model updating results are summarized in Table 5. Dimple stiffness is much higher than that of the spring, and the number of dimples per SG is normally twice as much as that of spring. So, the dimple can have more effect on the stiffness matrix than the spring. For this reason, it is explained that the dimple is more sensitive to the dynamic characteristics of the FR than the spring. The mode comparison results after updating are relatively good compared to before updating. These are shown in Fig. 10.

The model updating process drastically decreased the stiffnesses of the dimples in the 2nd and 3rd SG. The decrease in cost function turned out to be insignificant after the 1st iteration.

Comparisons of natural frequencies before and after model updating are shown in Table 6, which shows good agreement of EMA and values after model updating.

Table 5. Model Updating Results for Spring Constant vs. Iteration No. (S-Spring, D-Dimple)

No	Type	Model Value	1st Tune	1nd Tune	3rd Tune	No	Type	Model Value	1st Tune	2nd Tune	3rd Tune
1	S	1.53E5	1.53E5	1.53E5	1.53E5	9	D	8.84E6	6.41E5	5.78E5	5.24E5
2	〃	1.53E5	1.53E5	1.53E5	1.53E5	10	〃	8.84E6	1.77E6	1.83E6	1.93E6
3	〃	1.53E5	1.53E5	1.53E5	1.53E5	11	〃	8.84E6	2.58E6	2.84E6	3.14E6
4	〃	1.53E5	1.53E5	1.53E5	1.53E5	12	〃	8.84E6	6.98E6	6.86E6	6.64E6
5	〃	1.53E5	1.53E5	1.53E5	1.53E5	13	〃	8.84E6	7.91E6	8.09E6	8.09E6
6	D	8.84E6	5.79E5	5.62E6	5.47E6	14	〃	8.84E6	1.06E7	1.17E7	1.8E6
7	〃	8.84E6	5.08E5	4.85E6	4.64E6	15	〃	8.84E6	1.02E7	1.1E7	1.05E6
8	〃	8.84E6	1.38E6	1.4E6	1.41E6	-	-	-	-	-	-

Table 6. Comparison of FE Analysis with Before and After Model Updating

Mode No	After(Hz)	EMA(Hz)	Error(%)	MAC(%)
1	35.5	35.2	0.89	76.5
2	44.64	46.4	-3.70	44.1
3	52.8	49.2	7.44	95.9
4	88.9	88.6	0.33	55.2

5. Summary and Conclusions

Vibration analyses of a fuel rod supported by two different SGs was performed by both numerical and experimental methods. From the numerical analyses, higher natural frequencies for the FR with the type A SGs were obtained compared to those with the type B SGs. It is believed that the dimple increases the stiffness of the FR with SGs more than the spring does. However, from the experiment, lower natural frequencies for the type A SGs were obtained, in contrast to numerical analyses. The MACs for the both SGs are very similar. The values from odd(first and third) modes are relatively high as compared with even (second) modes. It was found that the modal parameters (natural frequency and mode shape) are very sensitive to the dimple stiffness of a SG.

Model updating was done on the spring and dimple stiffness, and modified dimple constants were obtained from that. However, since the SG was manufactured under well-controlled processes and conditions, it is impossible to physically explain such a large degradation of the dimple constant. The lower natural frequencies from EMA were believed to be partially due to the nonlinear characteristics of the spring, mainly mal-supporting conditions like the existence of some gap between the FR and the dimple while vibrating. It was found by a spring characteristic test that the SG spring showed linear characteristics within some force range and a nonlinearity beyond that[6]. The gap between the FR and SG is the worst Manufacturing condition because it is well known that such a gap easily accelerates fretting wear on the FR during operation, which consequently leads to failure of the FR. A collective action should be taken prior to loading the FR into a reactor even if a very small gap exists. Although the model update technique was originally aimed at enhancing the reliability of the FE model, for a system like a nuclear FR the technique can be employed during manufacturing to identify whether the FR is well supported by the SG or not.

Acknowledgement

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