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Preliminary Study on the Vibration Analysis Modeling for the New Cross-sectional Configuration of a Nuclear Fuel Rod

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1. Introduction

A new cross-sectional configuration, "doughnut-shape", of the PWR nuclear fuel was proposed. The new design, which is originally devised by Pavel Hejzler of MIT, is to boost amount of energy that nuclear reactor produce by 50 %, helps reduce the possibility of fuel meltdown by decreasing temperature at which reactor must be operated and it makes the spent fuel more proliferation-resistant [1]. From the structural design viewpoint, the PWR nuclear fuel should maintain structural integrity under normal and accident reactor operating conditions and its natural frequencies mismatch with the external excitation frequencies in operating reactor core [2, 3]. Thus, accurate prediction of the vibration characteristics of the nuclear fuel rod is essential task for the nuclear fuel design and development. However, the predictive modeling for this fuel rod is not easy because its dynamic behavior depends on various complicated issues such as variation of the support conditions of the rod due to irradiation, the contact condition between UO_2 pellet and cladding according to the burnup process and the flow condition including the severe thermal-hydraulic environment in the reactor internal core. In this paper, preliminary study on the vibration analysis modeling for the new cross-sectional configuration of the nuclear fuel rod is discussed. Simplification and assumption used in finite element (FE) modeling for annular fuel will be applied to the further predictive modeling and simulation for the newly developed nuclear fuel and its components.

2. Predictive Modeling and Results

The conventional PWR fuel rods(4 m long, 9.5 mm diameter) consists of UO_2 cylindrical, stacked pellets and a compression coil spring encapsulated within a cladding tube sealed welded with end caps. The fuel rod was supported by the 8~11 spacer grids spring and dimple along its length. Figure 1 shows schematic cross sectional configurations of the present PWR fuel rod and the newly proposed annular fuel. The annular fuel has a pellet annulus in-between two cladding tubes over the fuel cross-section tubes and the coolant flows inner and outer flow region simultaneously. The cross-sectional dimensions of annular fuel in this study referred to the previous work [4] on the study of fuel array and dimension compatible with present PWR reactor core. The supporting conditions for annular fuel rod were assumed to be same as those of the conventional PWR fuel rod. But the present supporting concept should be changed to meet the functional requirement as a rod supporter for the new dimension of annular fuel. Half-length (2.2 m) rod model was used as the analysis model for this study.

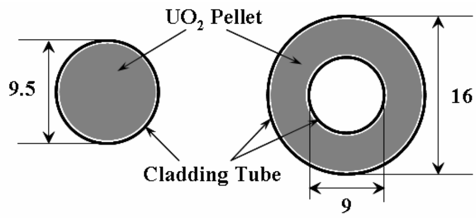


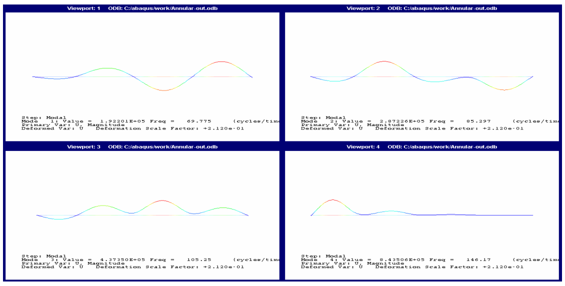
Figure 1. Schematic cross-sectional configurations of PWR fuel rod and annular fuel.

The FE model for the four-span annular fuel was based on the model, which is proposed by Kang [5, 6], for the conventional PWR fuel rod which is verified thoroughly with the test results. A commercial FEA code, ABAQUS, is used for FE modeling and analysis. A planar beam element (B21) that uses linear interpolation is used for the fuel rod and a connection element for the spring and dimple of the SG. For the numerical modal analysis, the Lanczos method is used to extract an eigenvalues and eigenvectors of the fuel rod. The linear characteristics of the spring and dimple were obtained by bending tests using a universal test machine. Added mass was considered in material property modeling of the fuel rod by the equivalent density. The damping and the effect of the friction between the rod and the SG in the FE analysis are ignored.

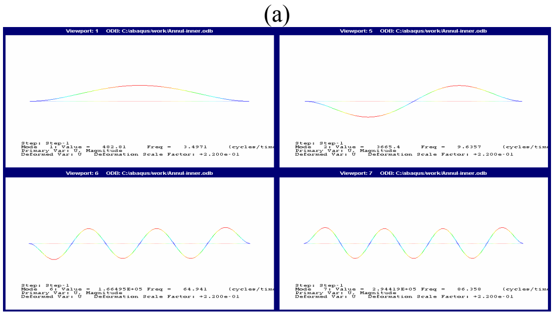
The contact condition between the pellet and inner/outer cladding tubes changes the vibration characteristic of the fuel rod according to the fuel burnup process. At the beginning of life time, the pellet detaches from the neighboring cladding tubes; this condition is an open gap. The pellet rigidity will not much influence on bending stiffness of the overall fuel rod. As the fuel burnup is processed, the clearance become smaller. At the end of fuel life time, pellet and claddings sticks each other; this case is a closed gap. The pellet stiffness dominates the rigidity of the fuel rod in this case. Accordingly, two cases for this problem were assumed according to the fuel life time in this study. The real condition of the fuel rod is in-between of these two cases. We analyzed the above two cases of the rod vibration modeling as following.

2.1 Multi- span outer tube and single span inner tube

For the case of the open gap, an outer tube of annular fuel are supported by the 5 spacer grids, while a inner one is supported by the end caps connected with outer tube. Thus, the annular fuel can be modeled as two individual tube models with different boundary conditions, but the pellet mass was assumed to be divided equally to two individual tubes. Figure 2 shows the analysis results (mode shape and natural frequency) for the multi-span outer tube and single span inner tube. The fundamental natural frequency of outer tube increased by 30 Hz compared to the present PWR solid fuel [5]. And a single-span inner tube has very lower values of natural frequency, even below 5 Hz. The inner tube's mode shapes corresponding to the frequencies near the outer tube's natural frequency are high-order bending mode above 7th order, which can coupled with the mode of outer tube.



(a)



(b)

Figure 2. Vibration analysis results of the open gap annular fuel rod;(a) multi-span outer tube, (b) single span inner tube.

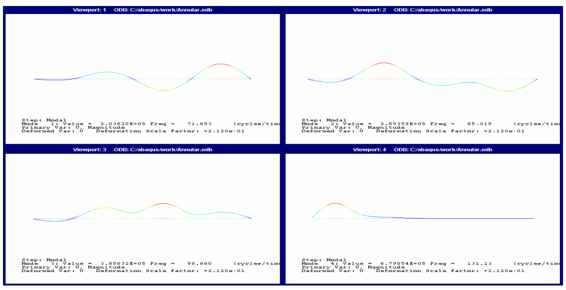


Figure 3. Vibration analysis results of the closed gap annular fuel rod with 5 spacer grid supports

2.2 Solid annulus of annular fuel

For the closed gap, the fuel rod cross-section can be modeled as a solid annulus with the thickness of 0.35 mm, which is the distance from inner diameter to outer diameter. Figure 3 shows the analysis results for the model of solid annulus of annular fuel. The fundamental natural frequency is 71 Hz and the mode shape is quite similar to previous solid one in spite of large difference of bending stiffness. But, this modeling scheme was too conservative when considering the gap between pellet and cladding.

3. Conclusion

Based on the FE vibration analysis model for the present PWR fuel rod, preliminary study on the free vibration of the annular fuel supported by 5 spacer grids was carried out. For the model of open gap, the multi-span outer tube had the same mode shapes as the solid PWR fuel rod, but the natural frequency increased by about 30 Hz. And a single-span inner tube has very lower values of natural frequency. For the closed gap, the annulus tube has similar mode shapes to those of the outer tube of open gap, and the fundamental natural frequency was 71 Hz. Further verification of this FE model for annular fuel is needed, but the simplification and assumption methodology used in FE modeling will help further predictive modeling and simulation. For the compatibility of annular fuel to present PWR reactor core, the discrepancy in natural frequency of the annular fuel rod should be adjusted by changing present supporting design unless the reactor core is redesigned. Thus, the number and spacing of these grids must be also re-designed so that the natural frequency of the fuel rod can escape the resonance from the external source of excitation in the present PWR reactor core.

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