



Nonlinear empirical model to simulate displacement-dependent structural behavior of a PWR fuel assembly



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ABSTRACT

A nonlinear model of a pressurized water reactor (PWR) fuel assembly is developed, and its performance is evaluated. The nuclear fuel assembly experiences numerous friction forces developed in the fuel rods and supporting components. Therefore, the fuel assembly deflection generates slips between the structures and develops a nonlinear behavior. The loose joints make it impossible for the rods to share a common center of curvature when the fuel assembly is deflected. In addition, when the fuel assembly is under a high temperature coolant water condition, the slip is activated because of the associated dimensional change. Thus, local and global displacements are introduced to compensate for the slip, and the relationship between the two is explained. Considering the fuel becomes soft when it is deflected, a nonlinear beam model with the varying second moment of area is proposed. The Galerkin discretization method is utilized to solve the nonlinear equation of motion, and an incremental solution is determined based on the linearized equation. Verification examples are provided, and the results are compared to the test data. It is shown that the concept of the model is reasonable and applicable. The developed model could be helpful to understand the nonlinear behavior of a fuel assembly and to predict the responses in case of an accident.

1. Introduction

When nonlinearity in a structure is negligible within the operating range of interest, a linear model is categorically preferred owing to its simple handling. Except under limited circumstances, nonlinear structural behaviors are commonly observed in various types of industries (Rhoads et al., 2010; Cigeroglu and Ozguven, 2006; Fessesse et al., 2004). Particularly, in the field of structural design, nonlinear finite element analysis is an extremely powerful tool for solving nonlinear problems using advanced computer technologies and algorithms (Lemaître, 1985; Weeger et al., 2014; Reddy, 2004). Because a direct solution of a nonlinear problem is rarely obtainable, linearization and iterative methods are the key to solving such a problem. Typically, the Newton-Raphson method (Reddy, 2004) is utilized to determine nonlinear solutions, and several efficient line searching algorithms have been developed to find an optimal solution (Bazaraa et al., 1993).

Because a nuclear power plant is a massive assembly of systems and structures, it can be inferred that nonlinearity will probably be present in the plant. Indeed, nonlinear behaviors are frequently found in a power plant, and these are mainly caused by friction, contacts, gaps, and local plastic deformations (Hassan et al., 2003; Kirk et al., 1982; Park et al., 2011; Molnar et al., 1976). Particularly, in case of seismic

events or loss-of-coolant accidents, the relatively large displacements occurring during the accidents cause the nonlinearities in the structures to become apparent. It is mandatory to evaluate the structural design margin under such conditions, and reliable models should be used for this purpose. The structure of the reactor in a plant is quite complex, and therefore, conservatively simplified models are preferred for low computational costs. Molnar et al. (1976) showed that the reduced degrees-of-freedom reactor model using the normal mode superposition is successfully applicable.

The geometries of the reactor internals including the nuclear fuel assemblies are also in complex, and thus, a simplified structural model is used to evaluate structural integrity against unwanted accidents. Although, a model may be simple, it should have high performance to ensure reliable results. Therefore, a model validation procedure is required, and the quality of the nuclear fuel assembly model should also be guaranteed. Ricciardi and Boccaccio (2014) conducted hydraulic loop tests and identified the mechanical parameters of the nuclear fuel assembly using a proper orthogonal decomposition method. They reported that the fuel stiffness is dependent on the flow rate. In their another work (Ricciardi and Boccaccio, 2015), they showed that the proposed fuel assembly model reasonably reproduced the experimental results, and inferred that by-pass flows affected the fuel assembly

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dynamics.

When the fuel assembly in a reactor is subjected to severe conditions such as earthquakes, it is mandatory that the proper geometry of the fuel assembly is maintained to allow the insertion of the control rods. Therefore, fuel vendors are required to measure the integrity of the fuel under accidental conditions. The structural integrity can be evaluated via numerical calculations as well as tests; therefore, conservative fuel models should be established. Fuel vendors perform a series of mechanical tests to identify or evaluate the fuel behaviors, and the results are used to develop reliable fuel assembly models. The authors in this paper have studied the mechanical behaviors of PWR nuclear fuels, and they noted that nonlinear behaviors were explicitly exhibited. They observed that the nonlinear load-deflection curves and variation of the natural frequencies depended on the lateral displacement. According to the experience of the authors, stiffness softening could be easily monitored during the tests.

This study deals with a nonlinear fuel assembly model for simulating the realistic mechanical behaviors of a fuel assembly. Noting that the fuel assembly becomes weaker during bending, a nonlinear mathematical model is proposed. Usually, structural nonlinearities are associated with the nonlinear material properties or with a remarkable geometric change (Reddy, 2004). The nuclear fuel assembly nonlinearity is due primarily to the fuel rod supports, which will be discussed later in the paper. Incremental solutions are obtained with the Newton-Raphson method, and the performance of the proposed model is compared with test results.

2. Nonlinear behaviors of a PWR fuel assembly

The fuel assembly of a PWR consists of hundreds of fuel rods that contain fissile material. The fuel rods are very slender, and they are loaded into spacer grids that provide lateral constraints (Park et al., 2011). The connection between the rod and spacer grid is not solid because the fuel rod must be replaceable in the event of an emergency. A spacer grid consists of numerous cells that accommodate the fuel rods, and the number of cells in the grid exactly matches the number of the fuel rods. It is by the friction forces between a rod and spacer grid cell that the array configuration is maintained throughout the life. When the fuels are exposed to high temperature reactor conditions, the grid cells cannot maintain a strong contact with the fuel rods due to the thermal expansion, and gaps can develop.

Fig. 1 illustrates a simplified fuel assembly configuration. Its entire length is approximately 4 m, and the width is approximately 0.2 m. Fuel rods are sustained with the spacer grids, and the two ends of the rod are free. The top and bottom nozzles are almost fixed in the reactor, and it is clear that the fuel assembly bending rigidity depends on the fuel rods as well as the guide thimbles. Fig. 2 is the test configuration to obtain load-deflection characteristics in air condition. One fuel assembly is loaded in the test facility that provide the same reactor boundary conditions. Two pins in each core plate are inserted into the top and bottom nozzle holes which is not shown in the figure. Then, the upper core plate holds down the top nozzle to prevent uncontrolled movements. Therefore, both ends of the fuel assembly are almost fixed. The actuator attached to the central spacer grid is required to apply a lateral load. Deflection of the fuel assembly can be measured with an LVDT (Linear Variable Displacement Transducer). The fuel assembly was instrumented with strain gauges which were mounted on the selected guide thimbles prior to the fuel rod insertion. Many strain gauges were used, but only a representative one is delineated in Fig. 2.

If the fuel is subjected to a lateral loading, a nonlinear load-deflection curve such as that in Fig. 3 can be observed. The loading point is located at nearly the center of the fuel assembly. The nonlinearity is clearly seen, and it is obvious that the stiffness is reduced. If the friction joints between the spacer grids and fuel rods are not strong enough to resist the motion, there should be slip. Consequently, when the fuel assembly is subjected to a bending motion, the supporting forces

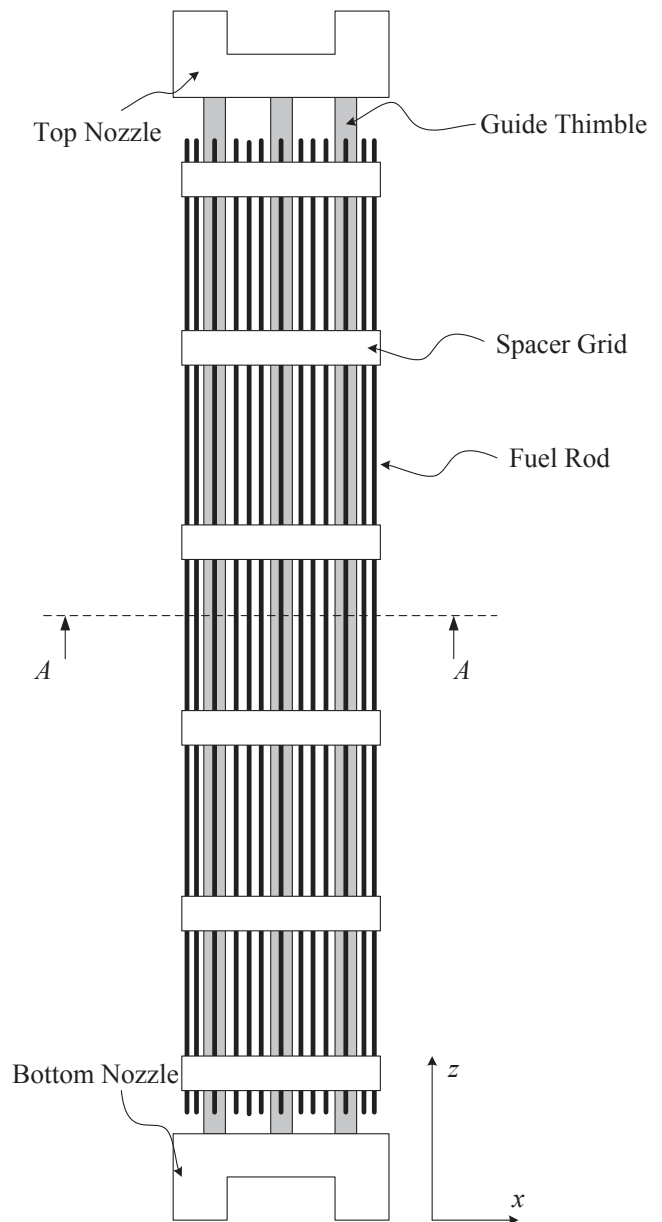


Fig. 1. Schematic of the PWR fuel assembly (See Fig. 6 for the view of A-A).

become weaker. Strain gauges are also attached along the guide thimbles, and Fig. 4 shows the measured strain in a guide thimble. Unlike the nonlinear load-deflection curve, the strain curve is approximately linear and less than a yielding point. All the other strain curves are similar to Fig. 4, therefore it is clear that the material nonlinearity is not relevant. It is noted that the strain curve on the fuel rods could not follow the same behavior because of the slip, nor will it pass the yielding point since the rods are much slender and more flexible than the guide thimbles. Although the strain curve on the fuel rod could behave nonlinearly, considering that the fuel rod and the guide thimble use the same metal alloy, it's not material dependent nonlinearity neither.

Free vibration can be monitored with the LVDT by removing the applied load suddenly. That is the central grid was deflected to a pre-determined value and then released abruptly. The actuator is only needed to provide the initial deflection. Upon reaching the point, the connecting rod of the actuator is detached from the fuel assembly. When the fuel assembly vibrates, the natural frequencies also vary. If the fuel assembly is promptly released from the given initial deflection,

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