Grid-to-rod flow-induced impact study for PWR fuel in reactor

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ABSTRACT

Dynamic contact impact from hydraulic flow-induced fuel assembly vibration is the source for grid-to-rod fretting in a pressurized water nuclear reactor (PWR). To support grid-to-rod fretting wear mitigation research, finite element analysis (FEA) was used to evaluate the hydraulic flow-induced impact intensity between the fuel rods and the spacer grids. Three-dimensional FEA models, with detailed geometries of the dimple and spring of the actual spacer grids along with fuel rods, were developed for flow impact simulation. The grid-to-rod dynamic impact simulation provided insights of the contact phenomena at grid-rod interface. It is an essential and effective way to evaluate contact forces and provide guidance for simulative bench fretting-impact tests.

Key words: PWR, flow-induced impact, grid-to-rod dynamic contact

1. Introduction

In PWR, the clearances between the contact surfaces of a fuel rod bundle and spacer grids increase due to radiation induced material aging and mechanical wear. Fluid turbulence leads to vibration of the fuel rod assembly, which in turn causes relative motions between the spacers and the fuel rods. The motion might be reciprocating sliding, impacting, or a combination of these. Ko [1] investigated the wear of zirconium alloys due to fretting and periodic impacting. Test results showed that the wear rate of superimposed reciprocating rubbing motions and periodic impact motions was many times higher than that of the wear due to each individual motion alone.

Mechanisms of flow-induced vibration and fretting in fuel channels have been studied and discussed by many researchers [2-7]. De Gee et al. [8] and Degli Espinosa et al. [9] researched the fretting wear under vibrational contact. Kim and Jang et al. [10] proposed three flow-induced vibration drivers acting on the grid-to-rod fretting wear in PWR fuel assembly. Bakosi et al. [11] conducted a series of isothermal turbulent flow calculations to understand the fluid dynamics of the flow-induced vibration problem leading to grid-to-rod-fretting. Most of the studies were based on and carried out through experimental investigations. Kim et al. [12] performed tests to simulate the flow-induced vibration of the fuel rods against springs and dimples and to study the fretting wear of a vibratory tube in the nuclear power plant. Jang et al. [13] conducted extensive fretting wear tests of the PWR fuel to evaluate fretting wear as function of grid-to-rod gap size under fuel rod vibration combined with high frequency grid strap

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vibration and fuel assembly vibration. Lu et al. [14] developed a testing and analysis methodology to investigate vibration and associated wear in nuclear fuel assemblies.

Flow-induced vibration is considered to be an important factor that can have significant impact on the fuel assembly life. Excessive vibration would induce intense fretting damage to the spacers and the fuel cladding. Grid-to-rod fretting (GTRF) wear is highly undesirable in the reactor operation. To support the grid-to-rod-fretting wear research for the purpose of minimizing fretting damage, it is important to evaluate the contact interaction between fuel rods and spacer grids under flow-induced contact-impact in reactor.

The contact forces used in previous wear tests for GTRF varied a lot. For example, in a study of the effect of impact frequency on the wear behavior of spring-supported tubes, Lee et al. [15] used a normal load of 10 N in the tests. Hong et al. [16] applied normal impact load 20-50 N on alloy 690 tubes in the tests to investigate impact fretting wear on the steam generator tubes against their support plates in nuclear power plants. Elmahdi et al. [17] used Large Eddy Simulation Computational Fluid Dynamic (LES CFD) analysis to estimate flow induced vibration forces and the calculated transient forces acting on the fuel rod ranged from 0.002 to 0.03 N. Choi et al. [18] used FEA to perform vibration analysis of a dummy fuel rod supported by spacer grids in PWR and estimated the forces of 0.25~1.25 N. Joulin et al. [19] set preloads from 0.1~2 N to study effects of loading conditions and type of motion on PWR fuel rod cladding wear.

This study investigated the grid-to-rod contact interaction for a pair of actual grid and rod under flow-induced dynamic impact in PWR using FEA simulation. Contact intensity estimated by FEA provided essential guidance to determine the loading in future fretting-impact wear bench tests.

2. FEA model for grid-to-rod flow-induced impact simulation

Three-dimensional models of the detailed dimple and spring structures at the spacer grids were developed for grid-to-rod flow-induced impact simulation, as shown in Figure 1. According to the targeted spacer grid design, there are two dimples on one side of a slot and one spring on the opposite side of the slot. Each dimple and each spring is an elongated member which arches from the associated grid strap inside the associated slot. Two dimples are modeled as arch-shaped members, where the flat section of the dimple is aligned with the fuel rod's surface contour in contact. Two dimples separate along the fuel rod axial direction at a distance of 21 mm. One spring is modeled as an arch-shaped member, which is 45 degrees diagonal to the fuel rod axial orientation. The surface profile of the spacer grid region was obtained using 3D white light interferometer (Wyko NT9100). The sketch was implemented in ABAQUS CAE to build the dimple/spring structure geometry. Thickness for both dimples and spring was 0.47 mm. The material of the dimple/spring is Zircaloy-4.

Dimple

Dimple-FEA model

Spring

Spring-FEA model

Figure 1. Three-dimensional FEA section models of Dimple and spring

Fuel rod with two dimples

Fuel rod with spring

Figure 2. Cross section view of the fuel rod with dimples/spring models

The PWR fuel rod was model as 356 mm long section including UO_2 fuel and Zircaloy-4 cladding. The length of fuel rod was an average length of a fuel rod between the spacer grids. The geometry of the cladding was modeled from physical dimensions with outer diameter of 9.47 mm and thickness 0.57 mm. Fuel was simplified as a rod instead of pellets with retaining the proper mass and acceptable inertial properties. Fuel diameter was fit with inner diameter of the cladding. Figure 2 shows the fuel rod section model with the detailed dimple/spring structures. Along the thickness of dimple/spring, there were three

layer meshes and mesh size was as small as 0.16mm. Within the region where contact between the cladding and dimple/spring occurs, there was a locally refined mesh in order to determine the reaction forces without excessive computational cost. There were totally 15450 and 15952 C3D8R elements for the fuel rod with two dimples model and for fuel rod with spring model respectively. The side surfaces of dimple/spring were linked to the space with some stiffness as boundaries to simulate intertwined spacer grid. Here the two dimples were assumed to have the same boundary conditions. Material properties used in the simulations are listed in Table 1.

Table 1. Mechanical properties of the fuel rod and spacer grid components

	Material	Young's modulus (GPa)	Poisson's ratio	Yield strength (MPa)	Density (kg/m ³)
Pellet	UO ₂ [20]	201	0.32	2,146	10,970
Clad, spring/dimple	Zircaloy-4 [21]	91	0.33	906	6,560

3. Grid-to-rod flow-induced impact simulation, results and discussion

The approach was to simulate fuel rod impact onto the dimples or spring within the spacer grids with a target impact velocity due to flow-induced vibration. The general contact algorithm was assigned at interfaces between the cladding's bottom surface and the top surface(s) of the dimples or spring with friction coefficient 0.3. The ABAQUS dynamic explicit code was used in this impact response analysis. In order to capture impact moment, the results were output in 2×10^{-5} s. Upon dynamic contact of the fuel rod and the dimples/spring, the contact stress and deformation of the interacting components (cladding, dimples, and spring) evolved progressively. Reaction forces at the contact surfaces were then estimated to evaluate the loading intensity of the target impact event.

Lu et al.[11] developed two major hydraulic loops, VIPER and VISTA to investigate flow-induced vibration. Vibration responses of the fuel rods induced by axial flow at various conditions were tested with bi-axial accelerometers. The test results showed that rod vibration amplitude ranged from 5-10 μ m, with modal frequencies ranged from 25-31 Hz for the first several dominant modes. The velocity of vibrating fuel rod upon impacting the spacer grids can be estimated from these test data as 0.25-0.62 mm/s. Since the testing was conducted in hydraulic loops, the estimated velocities of fuel rod took account of flow viscosity. Test results also showed that rods in the larger gapped cells have a higher vibration response than those in smaller gapped cells. Thus, FEA simulated the contact interactions for fuel rod impacting on to the dimples/spring with the estimated velocity of 0.25 mm/s as lower limit for smaller fuel rod vibration induced by axial flow at a smaller gap, and with the velocity of 0.62 mm/s as a higher limit for larger vibration at a large gap.

Figure 3 illustrates the progressive fuel rod impact on dimples with an initial velocity of 0.62 mm/s as example to show the contact interaction behavior between fuel rod and spacer grids of PWR during the flow-induced impact. The fuel rod traveled at a relative velocity of 0.62 mm/s towards the spacer grid dimples from a distance of 10 μ m. At approximately 1.66×10^{-2} s, the fuel rod was contacting with dimples. The velocity of the fuel rod kept changing during progressive contact interaction. Due to the rod's initial momentum, it moved forward continuously against the dimples until its momentum reduced to zero at 1.79×10^{-2} s. At this point, the maximum von-Mises stress of the dimple reached 0.722 MPa. Due to the dimple material's elastic recovery, the fuel rod started to bounce back. At 1.83×10^{-2} s, the contact stress level was reduced to that of the initial contact at 1.66×10^{-2} s. At 1.91×10^{-2} s, the fuel rod start losing contact with the dimples, and the system's stress level further decreased. When the fuel rod

completely separated from the dimples, there were small residual stresses remaining in the fuel rod and spacer grids. In this study, SI unit was used. Here the stress is in Pa.

Figure 3. The progressive evolution of a fuel rod impact onto dimples at the velocity of 0.62mm/s

Figure 4. Contact pressure and stress distribution during fuel rod's impact on dimples

The contact pressure and stress distribution during the fuel rod's impact onto the dimples are shown in Figure 4, for the lower end of 0.25 mm/s and higher end of 0.62 mm/s impact velocity. The maximum contact pressure on the dimples reached 0.380 MPa upon fuel rod impact at velocity of 0.25 mm/s. The maximum von Mises stress on the clad occurred at the locations where the clad contacted the dimples. The maximum Von Mises stress on the clad was 0.107 MPa, which was less than the yield stress 906MPa, for an impact velocity of 0.25 mm/s. Neither the fuel rod nor the dimples yielded. When the impact velocity was set to 0.62mm/s, the contact pressure on the dimples reached a maximum value of 0.736 MPa, which is about 2 times greater than the contact pressure result from the lower limit impact velocity. The maximum von Mises stress on the clad was also doubled when compared to the stress from the impact at 0.25 mm/s. However, the maximum Von Mises stress of 0.256 MPa is less than the material yield stress in this higher speed impact simulation. The reaction forces were calculated by integrating contact pressures over the associated contact areas on the dimples. The calculated contact force on one dimple was 0.085 N for fuel rod impact at a velocity of 0.25 mm/s. For the impact velocity of 0.62 mm/s, the calculated contact force on one dimple was estimated as 0.236 N, which is 2.7 times greater than contact force from the 0.25 mm/s impact velocity.

It is speculated that the spacer grid slot has non-symmetric boundary condition, as shown in **Figure 5**, and the dimple at the slot side tends to rotate upon off-center contact of the fuel rod. For such a scenario the

dimple at the slot side was modeled with lower stiffness boundary than the dimple not at the slot side (Figure 5).

Figure 5. Part of spacer grid—dimples face up

Figure 6 shows the contact pressure and stress distribution during fuel rod's impact onto dimples with a non-symmetric boundary. It was observed that on the dimple with lower stiffness boundary there was no resultant contact pressure; while on the dimple with higher stiffness boundary, the contact pressure is 35% higher than that of dimples with the same boundary conditions in **Figure 4**. Thus, accordingly there was only one impact contact spot on clad and the maximum stress on the cladding is 34% higher than that in **Figure 4**.

Figure 6. Contact pressure and stress distribution during fuel rod's impact on dimples with non-symmetric boundary

Similar simulations were performed on the rod-spring impact caused by the flow-induced vibration at the lower and higher limit velocity of 0.25-0.62 mm/s. **Figure 7** shows the resultant contact pressure and stress distribution during the impact. For an impact velocity of 0.25 mm/s, the maximum contact pressure on the spring reached 0.311 MPa, which was 22% lower than the dimples at the same impact speed. The maximum Von Mises stress on the clad also occurred at the contact location with the spring. The maximum Von Mises stress on the clad was 0.616 MPa, which was 73% lower than the rod-dimple impact at the same velocity. With a higher velocity of 0.62 mm/s, the maximum contact pressure on the spring increased to 0.489 MPa, however it was 50% lower than the dimples contact pressure. The maximum von Mises stress on the clad increased to 0.142 MPa for the impact velocity of 0.62 mm/s, and it was 80% lower when compared to rod-dimple contact shown in **Figure 4**. The reason for the lower resultant stress level for fuel-spring impact is due to the lower stiffness of the spring compared to that of the dimples. Similarly, the maximum stress on the contact-system components for the fuel rod impact onto the spring was much lower than the material yield strengths listed in **Table 1**. Thus, it is expected that after the grid-to-rod system impact event, the rod and spacer surfaces would remain intact.

Figure 7. Contact pressure and stress distribution during fuel rod's impact on spring

The contact reaction forces estimated from the contact pressure on spring at the impact velocities of 0.25 and 0.62mm/s were 0.08 and 0.16 N, respectively. For the spring, the contact force doubled at the higher speed impact case. The estimated contact forces for all the impact simulations are summarized in Table 2.

Table 2. Contact forces from flow-induced fuel rod vibration impact

Impact	FEA estimated contact force (N)
Rod against spring	0.08 ~ 0.16
Rod against dimples	0.17 ~ 0.47

Comparing to vibration loading Choi et al. [18] and Joulin et al. [19] used in their studies for PWR, which were ranging from 0.25~1.25N and 0.1~2N respectively, the estimated impact loading in Table 2 are consistent in the force level. The flow-induced fuel rod vibration impact simulations provide guidance of the contact forces for future grid-to-rod fretting-impact wear bench tests.

4. Conclusions

Three-dimensional FEA models of fuel rods in contact against spacer grids were developed with detailed contact geometries of a PWR reactor. The simulations of fuel rod impact onto the dimples/spring within the spacer grids at targeted velocities were performed to study the grid-to-rod contact interactions. Results provide insights of grid-to-rod interactions upon impact due to flow-induced vibration. The related contact intensities were evaluated accordingly, which indicated that the fuel rod and spacer grids would remain intact after flow-induced impact events. Reaction forces quantified from contact pressure on dimples/ spring provided guidance for the contact forces to be used in future fretting-impact wear bench tests. **An autoclave fretting-impact bench tribometer are currently designed and fabricated with a load range of 0.1-1 N, which is based on the calculated forces in this study. When the machine is built, the rod-spring and rod-dimple contacts will be tested under loads at the low, middle, and high points of the estimated contact force ranges in Table 2.**

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