PWR fuel rod vibration simulation analysis for estimating grid-to-rod-fretting (GTRF)

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ABSTRACT

Fuel rods under reactor operating conditions are subjected to turbulence-induced fluctuations of forces that cause small amplitude vibrations in the rod and could lead to excessive grid-to-rod-fretting (GTRF) and wear of the cladding material. GTRF has traditionally been one of the most important failure mechanism of nuclear fuel assemblies.

The objective of the project that is described in this paper is to develop a methodology that simulates the GTRF wear process using computer codes. The methodology is based on the small amplitudes of the vibration, which allows a separated study of the flow forces and the fuel rod vibration. In the first step, a CFD Large Eddy Simulation is used to characterize the flow features affecting the rod vibration. The results obtained are then used in the second step as inputs for a FEA code which simulates the non-linear vibrations caused by the contact and friction forces. Finally, the wear of the cladding is estimated based on a semi-empirical formulation.

1. Introduction

Fuel assemblies in PWR nuclear power plants under reactor operating conditions are subjected to fluid forces due to the coolant mass flow. Turbulence-induced fluctuations of viscous and pressure forces induce small amplitude vibrations in the fuel rod that could lead to excessive grid-to-rod-fretting (GTRF) and wear of the cladding material.

As cladding is the second containment barrier of fission products, understanding factors and margins of GTRF is a relevant issue for nuclear fuel design. GTRF failures have dropped over the last few decades. However, the increased cycle length and burnup of new and more challenging operational scenarios (which seek the improvement of power plant economics), makes controlling GTRF critical to minimize fuel failures risk [1].

GTRF analysis constitutes itself an inherently multidisciplinary field of study that depends on complicated physical, thermalhydraulic, structural and tribologycal phenomena in complex fuel assembly geometries. Furthermore, time-varying boundary conditions and irradiated material properties, as creep, corrosion, stress relaxation at the supports or fuel rod bow, shows the difficult to fully resolve GTRF using computational methods.

Different studies and publications have been made to understand and modelling GTRF. References [2] and [3] model the dynamic behaviour of the rod with non-linear supports. References [4], [5] and [6] carried out CFD simulations to understand turbulent flows on fuel assembly and to determine the time history and statistics of the forces loading the fuel rod. Reference [1] collect studies of other factors affecting the GTRF that are not included in this project such as creep, swelling or corrosion. In addition, experimental surveillance and inspection programs has been implemented in nuclear power plants, such as the one of reference [7] from ENUSA.

According to different studies in the last years (references [8], [9]), the main factors affecting the GTRF are:

- Flow-induced vibration.
- Grid to rod support conditions (gap between rod and grid, spring and dimples forces).
- Initial grid to rod contact.
- Position of the rod inside nuclear core.

Regarding flow-induced vibration, three mechanism are identified for a fuel assembly:

- Turbulence-induced vibration.
- Self-induced vibration due to cross-flow in the fuel assembly
- Self-induced vibration of the outer straps of the grid.

The objective of the project that is described in this paper is to develop a methodology that simulates the GTRF wear process of one rod due to the turbulence-induced vibration using Computational Fluid Dynamics (CFD) and Finite Element Analysis (FEA) codes.

2. Methodology

The study case of a fuel rod under operating conditions is fairly complex from the simulation point of view, as it involves all the relevant physical phenomena mentioned above. Due to this fact, a fully coupled Fluid-Structure Interaction (FSI) simulation is not feasible within industrial constraints, as the computational resources needed are too expensive and time-consuming. Therefore, a different strategy has been proposed by ENUSA and the UPM (Universidad Politécnica de Madrid) to create a multi-step analysis method. The main hypothesis is that the vibrations that take place under nominal flow velocities are smaller than the ones related to fluidelastic instabilities. Moreover, the amplitudes of these vibrations (named subcritical or turbulence-induced vibrations) are relatively small. Consequently, the induced forces can be considered independent from the movement of the rod, which allows a separated study of the flow forces and the fuel rod vibration.

These fluid forces can be decomposed as a linear function of the structural motion in four terms related to the added mass, damping, rigidity and an external force independent of the movement of the rod (Equation 1). Therefore, the rod vibration can be studied as a mechanical forced vibration problem where the excitation term is caused by the fluid pressure fluctuations over the rod.

$$\{F\}_{fluid} = -\left[M_f\right]\{\ddot{x}\} - \left[C_f\right]\{\dot{x}\} - \left[K_f\right]\{x\} + \{G\} \Rightarrow$$

$$\left[M_s + M_f\right]\{\ddot{x}\} + \left[C_s + C_f\right]\{\dot{x}\} + \left[K_s + K_f\right]\{x\} = \{G\}$$

Where M_s, C_s and K_s are the inertia, damping and rigidity terms represented by matrices of a multi-degree-of freedom system; F the fluid force applied to the rod; M_f, C_f and K_f are the added mass, fluid damping and fluid rigidity matrix, G is the external force vector and x the vibration amplitude.

Equation 1. Fluid force and Differential equation which governs the vibration of the rod

In the first step of the method, a commercial CFD code (Star-CCM+ v12.04) is used to characterize the flow features affecting the rod vibration. A transient simulation with a LES turbulence model is carried out, as it is able to capture the pressure fluctuations which induce the relative displacement between rods and grids. The force time history over the rod is used to compute the Power Spectral Density (PSD) that characterizes the spectral components of the turbulent excitation force.

The results obtained from the CFD simulation are then used in the second step of the method as inputs for a commercial FEA code (ANSYS Mechanical APDL). A beam model of the rod which simulates the non-linear vibrations caused by the support impact forces (contact and friction) is performed.

Finally, in the last step, the wear of the cladding is estimated using the normal forces and the relative velocity at the grid-to-rod-contact based on a semi-empirical formulation. Figure 1 summarizes all the steps of the methodology.

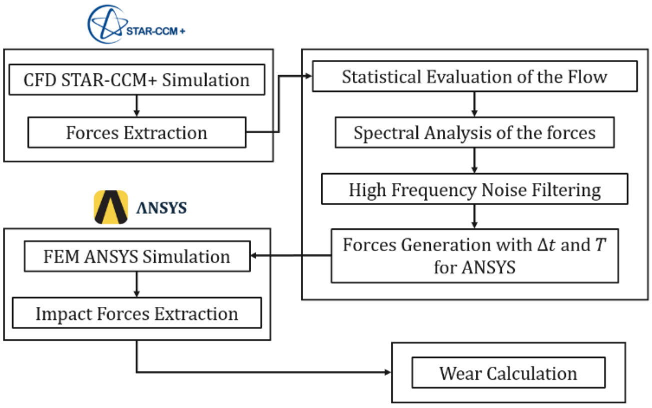

Figure 1. Methodology Workflow

2.1. CFD model

A CFD transient simulation is carried out to calculate fluid force fluctuations over the rod. These pressure fluctuations have a random behaviour over the time. The typical Reynolds-Averaged Navier-Stokes (RANS) turbulence models compute the flow statistics by solving only the mean flow field values; therefore, this approach it not useful to solve this problem and to be able to predict pressure fluctuations a Scale Resolving Simulation (SRS) turbulence model has to be employed.

Large Eddy Simulation (LES) can describe the unsteady, large-scale turbulent structures and can study the phenomena that drives GTRF (references [4], [5] and [6]). To adequately resolve the different turbulent structures, a small cell size must be used due to high Reynolds number, which leads to expensive computational cost. This issue limits the geometrical domain and time simulated.

The representative geometry used to calculate the flow over the rod is one span full grid cell (Figure 2). The final mesh is made of around 45 millions pure hexahedral elements (Figure 3). The adequate time step to the cell size and the fluid velocity is $2.5 \cdot 10^{-5}$ s. Uniform inlet velocity is used at the inlet and a pressure outlet condition at the exit. Since the geometry is a small part of the fuel assembly, periodic boundary conditions were applied. Fuel rods and grid surfaces are simulated as no-slip walls.

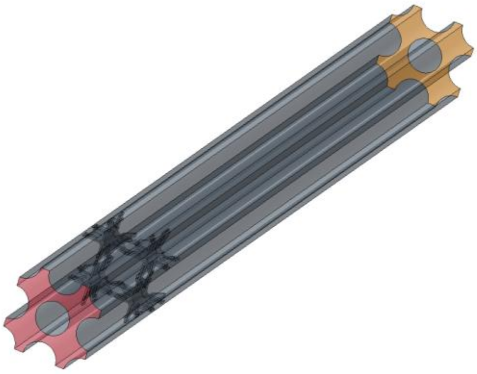

Figure 2. Geometry Domain

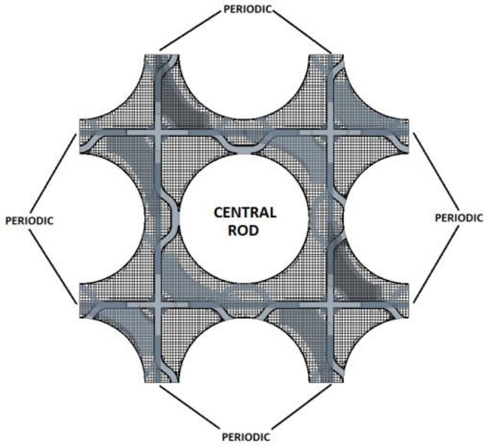

Figure 3. Mesh

The central rod of the model (Figure 2) is used to obtain the transient forces. The fuel rod is divided into 1 inch segments and the total force is calculated at each time steps in two lateral directions. Figure 4 shows these raw forces (without the spectral and statistical treatment from the following Section) as a function of time for the Y and Z directions (normal to the rod). Figure 5 shows the root mean square (RMS). It can be observed that the turbulent forces decay along the span downstream the grid, as the grid mixing vanes are the main source of these turbulence forces. Figure 6 shows lateral velocities in a cross section and velocities on Q-criterion isosurfaces around the central rod.

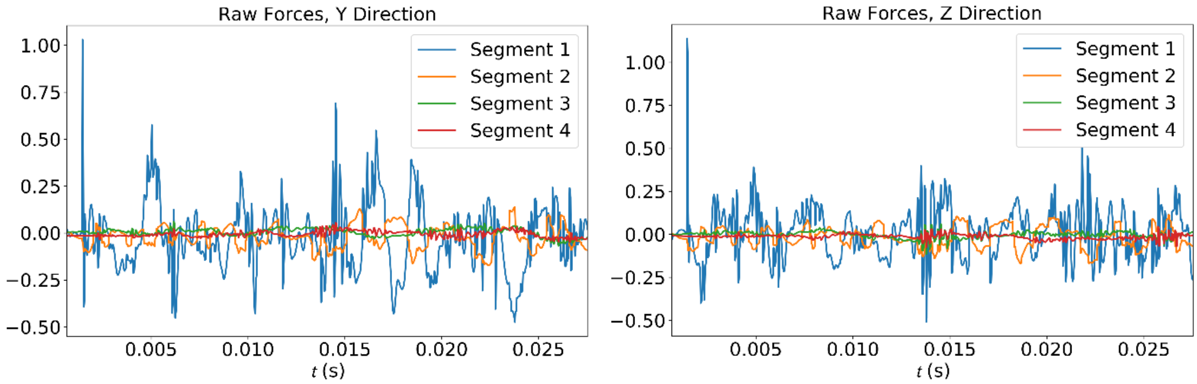

Figure 4. Raw Forces for several segments (N)

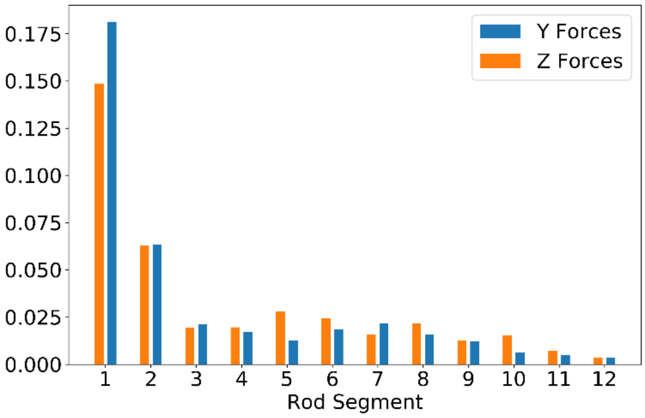

Figure 5. RMS forces for all segments (N)

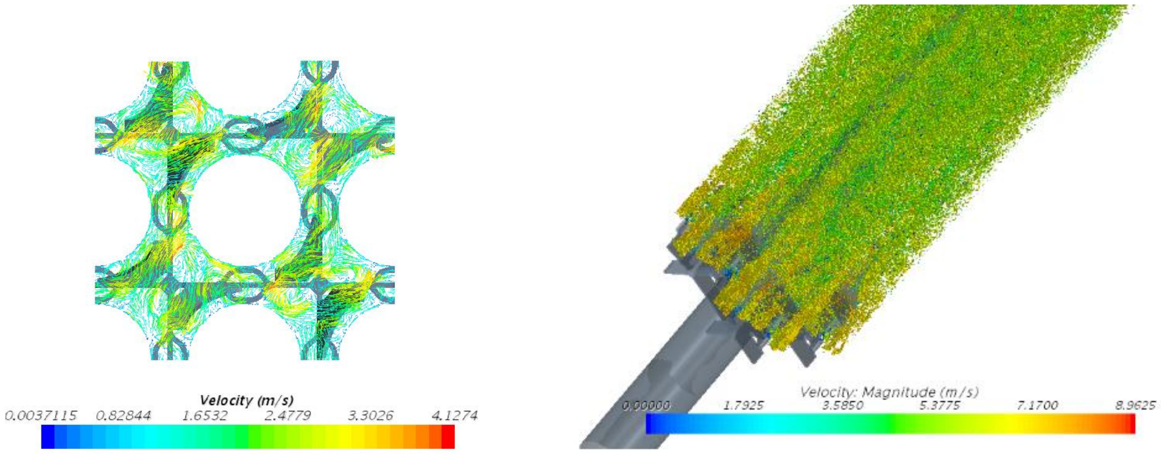

Figure 6. Lateral velocities and Q-criterion isosurfaces around the rod

2.1.1. Spectral analysis

The raw forces represented in Figure 4 cannot be directly applied as load conditions to the FEA model due to four reasons. First, the time step employed in the CFD simulation was kept small to adequately capture the turbulence-induced vibrations ($\Delta t \sim 2.5 \cdot 10^{-5}$ s), which is prohibitively small to model the vibration of the rod and therefore it has to be averaged. Second, only one rod span was simulated, and consequently it is necessary to expand the force values to the rest of the rod spans. Third, it is convenient to filter the high-frequency components of the force because they contain less energy than the rest. Finally, as it can be observed in Figure 4, the CFD simulation covers only thousandths of seconds, and appreciable wear can only be observed in a greater period of time.

PSDs of the forces are used to generate an equivalent harmonic signal. Figure 8 shows the PSD for the first segments. As it can be seen, the power of the signal is reduced with rod segment (as in Figure 5), and it tends to decrease for frequencies higher than 2000 Hz for the first two segments.

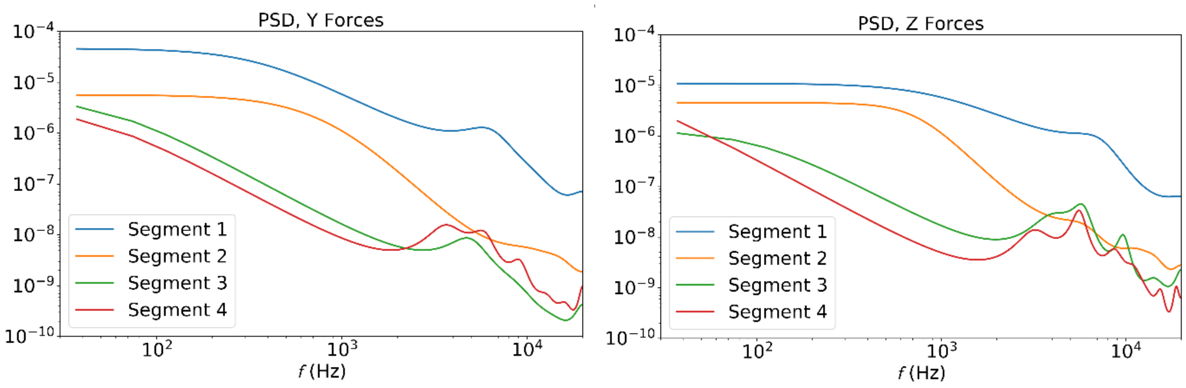

Figure 8. Power Spectral Density (PSD) for several segments (N^2/Hz)

Once the PSD is obtained, high frequency components can be filtered, so that the final force retains the spectral components which complies with a maximum frequency. This methodology leads to an equivalent harmonic signal which is a linear combination of sines and cosines (the low-frequency Fourier harmonics), and thus can be indefinitely extended in time. As Figure 9 shows, the equivalent signal has similar spectral properties in the low-frequency region while respecting the general time features of the raw signal and being defined for all t. As the correlation between each segment forces are low (from 0.14 to 0.57 for adjacent segments and much lower for the rest of segments, using Pearson correlation coefficient), these equivalent forces are calculated for each segment.

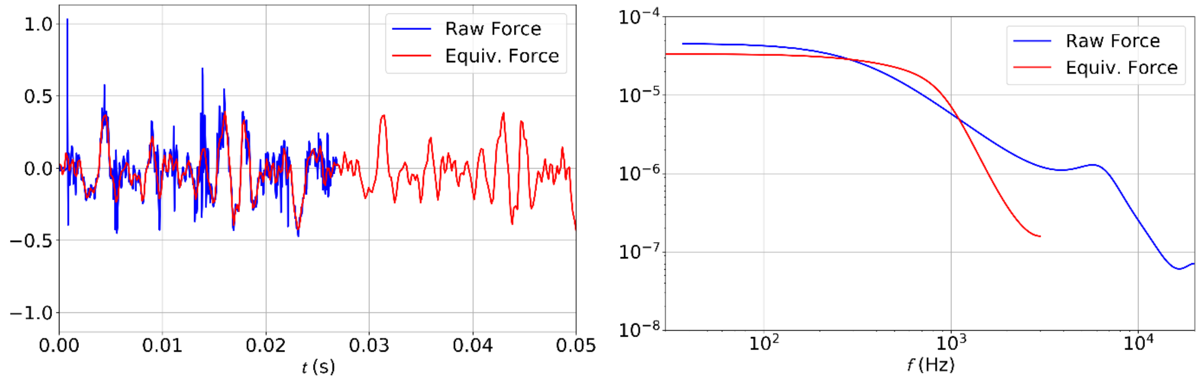

Figure 9. Raw and equivalent signal for the Y Force in the 1st segment. Left: Force (N). Right: PSD (N^2/Hz)

2.2. FEA model

The FEA model predicts the movement of the rod using the time history forces obtained from the spectral analysis described in the previous section and taking into account preloads and gaps between rod and grids. The wear rate is obtained from the impact forces (normal and friction) in the supports.

ANSYS Mechanical 17.2 is used to perform a time-transient analysis that resolves the full system matrices to calculate the transient response at each solution point without using vibration mode superposition. This approach implies a higher computational cost but it allows to calculate all the non-linear effect due to the rod vibration caused by the impact forces. The fuel rod is modelled as a beam element, while springs and dimples of each grid are modelled as node-to-node contact elements.

Springs and dimples are modelled using the Pure Penalty Method, which introduces a force in each of the contact surfaces with the purpose of eliminating the penetration. The normal force is represented by equation 2, where K_N is the stiffness of the spring or the dimple of the grid and U_N is the distance between the nodes, having considered the initial gap.

$$F_N = \begin{cases} F_N = 0, & U_N > 0 \\ F_N = K_N U_{N,} & U_N \leq 0 \end{cases}$$

Equation 2. Normal Force

The tangential forces are calculated using the friction coefficient μ. The tangential force (F_{sy} or F_{sz}) depends on if the maximum friction force is achieve, as it is shown in equation 3, where K_S is the tangential stiffness and U_s the tangential displacement.

$$F_{sy} = \begin{cases} F_{sy} = K_S U_S, & \sqrt{F_{sy}^2 + F_{sz}^2} - \mu F_N > 0 \\ F_{sy} = \mu K_N U_{N,} & \sqrt{F_{sy}^2 + F_{sz}^2} - \mu F_N = 0 \end{cases}$$

Equation 3. Tangential Force F_{sy}

The excitation forces obtained from Spectral Analysis are introduced in each segment (12 segments for each span). Figure 10 shows a sketch of the APDL mechanical model.

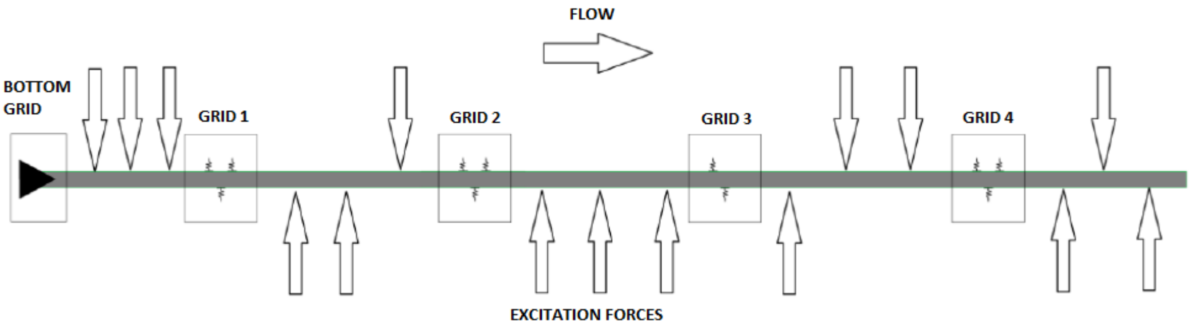

Figure 10. ANSYS APDL Rod Model with four grids

Figure 11 displays the Y and Z deflections and forces for a certain time step of the simulation. Dimples have been represented as filled triangles and springs as empty triangles. The values are in the order of the normally rod vibration, [11].

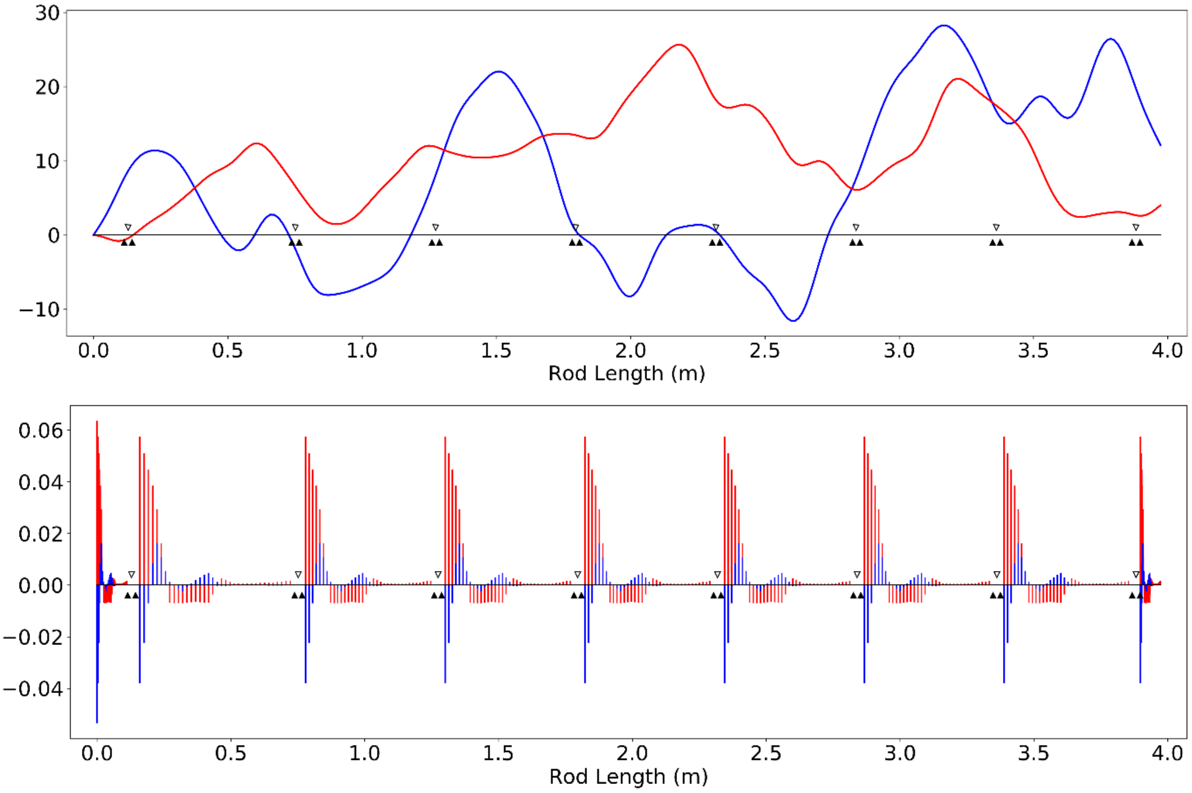

Figure 11. Y and Z Rod Deflection (Up, µm) and Y and Z Forces (Down, N)

2.3. Wear model

Once the simulation is completed, wear is computed employing the Archard Law (reference [10]) for each loading direction:

$$\dot{W}_Y = K(E)[R_Y(t)]^n\,[v_Y^{\perp}(t)]^m, \qquad \dot{W}_Z = K(E)[R_Z(t)]^n[v_Z^{\perp}(t)]^m,$$

Equation 4. Wear Archard's Law

where $\dot{W}$ is the wear rate (m^3/s), K is the wear coefficient (Pa^{-1}), E is the wear energy (the integral of the wear power, $P = R(t)v(t)$), R is the reaction in the support (N) and $v^{\perp}$ is the velocity normal to the reaction (m/s). Equation 4 is integrated in time to obtain the accumulated worn volume (m^3), and it is then expressed in terms of the equivalent depth of the wear scar (μm) employing geometrical considerations.

An example was calculated using estimated material parameters for the equation 4. Figure 12 shows an estimation for the fretting wear scar depth for the bottom grid. It can be noticed how wear rate is far from constant, as wear increases only when the displacement of the rod in the contact is high enough to exceed the gap. Assuming a linear wear rate of $3 \cdot 10^{-8}$ μm/s, and extrapolating the validity of the turbulence conditions during three cycles of irradiation, an equivalent scar of around 4 μm would appear, which is in the order of magnitude of the inspections performed [7].

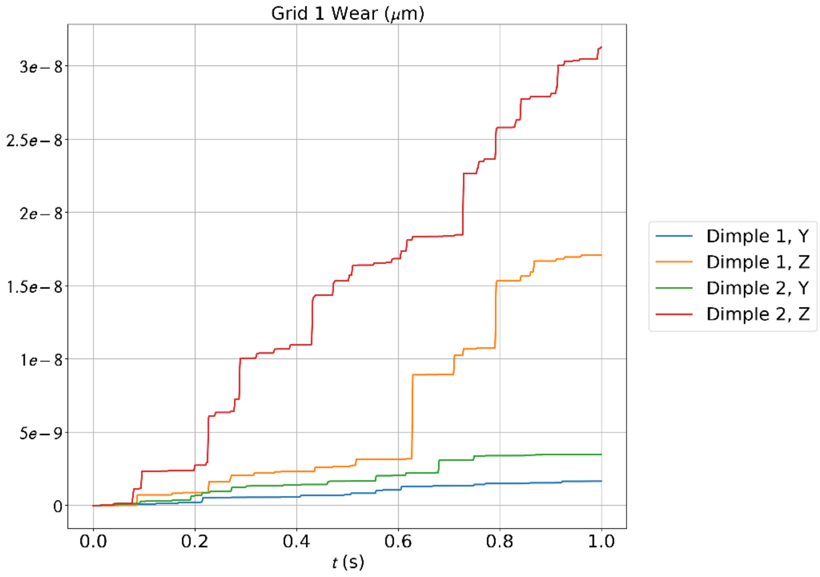

Figure 12. Fretting Wear in the Bottom Grid in each dimple and direction (μm)

3. Conclusions

GTRF is a complex mechanism that involves interaction between the fuel rods, spacer grids and coolant flow. As a conclusion, in this project it was found that it is possible to reasonably estimate the GTRF without a full fluid-structure simulation, using the multi-step method developed by ENUSA and the UPM. A linear wear rate can be assume from the simulations and extrapolating the validity of the turbulence conditions during three cycles of irradiation an equivalent scar of around 4 μm would appear, which is in the order of magnitude of the inspections performed.

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