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VITRAN CODE – PWR NUCLEAR FUEL ROD FLOW INDUCED VIBRATION SIMULATIONS

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ABSTRACT
Grid-to-Rod Fretting (GTRF) wear is one of the main causes of fuel rod leaking in PWR reactors. Significant design improvements for Westinghouse PWRs have been made to eliminate this cause. GTRF is a complicated combination of several physical phenomena including flow turbulence excitation, fuel rod non-linear structural vibration and fretting wear process (tribology). Developing fretting simulation code and methodology have been challenging tasks for researchers and engineers. This paper presents fretting wear simulation methodology and results with the VITRAN (Vibration Transient Analysis Non-linear) code. VITRAN is a code developed by Westinghouse. The code is used to simulate non-linear vibration of a nuclear fuel rod and dynamic interaction between the fuel rod and supports. The code also integrates a GTRF analysis method to predict GTRF performance. Turbulence forces due to spacer grids and mixing vanes, as well as axial flow are excitation force inputs for the code.

1. INTRODUCTION
Grid-to-Rod Fretting (GTRF) wear is currently one of the main causes of fuel leakage and is responsible for over 70% of the fuel leaking in pressurized water reactors (PWRs) in the U.S. Fuel rods in the fuel assembly are supported by the springs and dimples of the spacer grid. As the coolant flows through the fuel assembly, fluid forces generated by the flow field would induce vibration on the fuel rod. Flow-induced vibration causes small relative motions between the supports and the fuel rod, leading to fretting wear. As irradiation creep and growth take effects, the preloads of the rod support springs relax with time, and the plastic deformation in the spacer grid and fuel rod becomes more significant, causing geometry changes (e.g., cladding creep-down and spacer grid growth). Under these conditions, the spring and dimple supports might lose preloads with the fuel rod, leading to the formation of gaps between the spacer grid and the fuel rod. This magnifies the effects of flow-induced vibration and causes cyclic contact forces, both normal and tangential, between the spring-dimple supports and the fuel rod, which results to fretting wear. Thus, predictive simulations of GTRF involve turbulence flow, structural dynamics, contacts and wear. In addition, the changes in the mechanical behavior and wear characteristics of the materials in the irradiation environment during reactor operations have a direct effect on the GTRF mechanisms.

In the following, state-of-the-art modeling methodology developed by Westinghouse to address GTRF will be described.

2. VITRAN CODE MODELING TECHNOLOGY
VITRAN (VIbration TRansient Analysis – Nonlinear) is a special code developed by Westinghouse to simulate flow-induced vibration and fretting wear of a PWR fuel rod [1, 2 and 3]. VITRAN integrates hydraulic, nonlinear structural and tribological effects. The model takes into account the presence of rod-to-grid gaps that may develop as result of the cladding creep-down, spring relaxation, grid growth, wear effects, etc. VITRAN calculates the rod frequency response and motion, the support impact forces (normal and friction forces), the sliding and sticking distances and the work rates. The model uses the normal work rate to calculate the rod wear rates and the scar depths according to the wear coefficients and the geometric characteristics of the pair rod-support. Figure 1 shows the

structure of VITRAN code. VITRAN includes statistical analysis modules that can be used with Monte Carlo simulations and are particularly useful to take into account the large uncertainties existing in most of the mechanical parameters of the fuel assembly and its boundary conditions as shown in Figure 2.

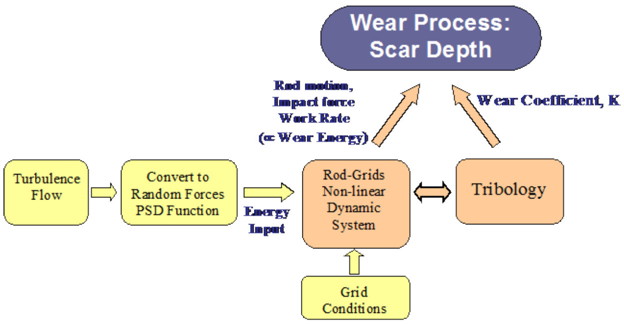

FIGURE 1: THE STRUCTURE OF VITRAN CODE

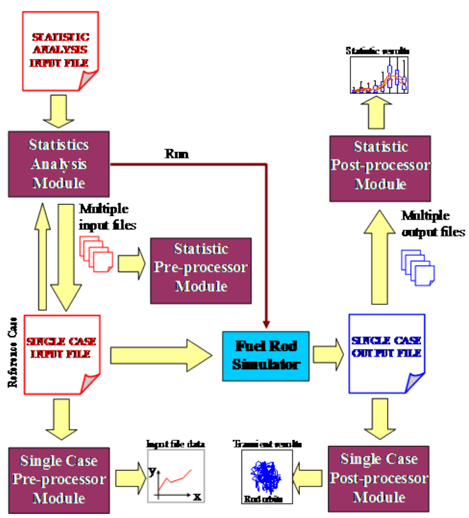

FIGURE 2: VITRAN STATISTIC MODULES

2.1 SINGLE FUEL ROD MODEL AND FLOW INDUCED EXCITATION FORCE

A full length fuel rod model for a Westinghouse standard fuel assembly design is shown in Figure 3. The fuel rod has six mid spacer grids. Each support grid cell can have positive preloads or gaps to the fuel rod to simulate the beginning of life or the end of life conditions. The alignment of each grid cell relative to the fuel rod is also a parameter in the code inputs.

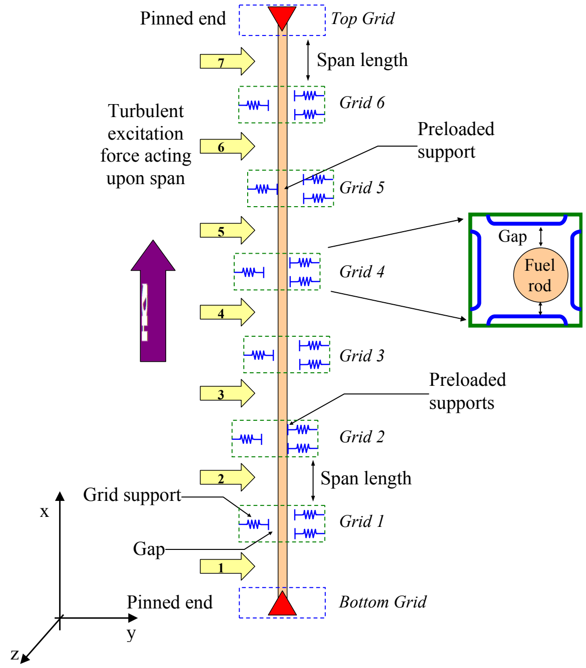

FIGURE 3: A FULL LENGTH FUEL ROD MODEL WITH SIX MID SPACER GRIDS

Reactor coolant flow with high velocity and turbulence removes heat generated by fuel rods in a PWR reactor core. High flow velocity and turbulence imposes stochastic and fluctuating pressure (force) on the fuel rod surface and induces fuel rod vibration. Also, other excitation forces exist in reactor environment. The VITRAN code has flexible force input formats and can have different excitation force input formats as well as their combinations. The force formats are 1) the concentrated white noise random force; 2) the concentrated sinusoidal force; 3) the random force with even distributed PSD (Power Spectrum Density) along spans; 4) the random force with arbitrary PSD profile along spans.

3. BENCHMARK AND SIMULATION

3.1 ROD VIBRATION BENCHMARK

To obtain the flow excitation force function, a series of fuel rod vibration tests were performed in the Westinghouse FACTS (Fuel Assembly Compatibility Test System) hydraulic loop. In the test, all grid cells were as-built conditions and fuel rods were well supported with preload. The fuel rod and supports are close to a linear system, which simplified nonlinear effect (e.g., gap effect). Several instrumented fuel rods were used to measure fuel rod vibration. Each instrumented fuel rod contained a bi-axial accelerometer at a certain elevation. Annular tungsten-carbide bushings were used in place of uranium pellets to allow routing of the accelerometer leads through the rod. The linear weight of the tungsten-carbide bushings was the same as that of the uranium pellets to reserve the dynamic characteristics of the fuel rod.

Loop flow velocity was increased from 2 m/s to 6.5 m/s with a small increment during the test. Fuel rod acceleration and displacement signal in the time domain were recorded at each test flow rate step.

The VITRAN fuel rod model for this particular test is similar to that shown in Figure 3 except all grid cells are at as-built conditions with pre-loads. Figure 4 shows the comparison of acceleration frequency spectrum of test results from an instrumented rod and VITRAN simulation results. The comparison of Figure 4 demonstrates VITRAN simulation has very good agreement with FACTS test data on the characteristics of the rod vibration frequency response. It also shows that the vibration responses above 100 Hz are relative small for as-built cell conditions. It can be concluded that turbulence flow above 100 Hz has small contribution to fuel rod vibration or turbulence force (model and test) and that rod vibration is not excited at higher modes (above 100 Hz).

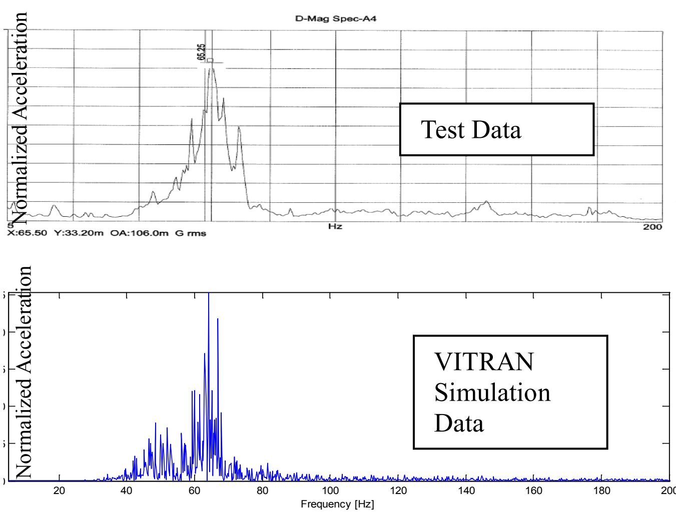

FIGURE 4: ACCELERATION FREQUENCY SPECTRUM COMPARISON

By simply tuning one constant parameter (the magnitude of PSD) in the PSD function, VITRAN simulation results can get very good agreement with the test results, as shown in Figure 5, where the amplitudes of fuel rod mid span accelerations are compared. VITRAN results agree with the test results on both the amplitudes and the tendency of amplitude change with flow rate increase.

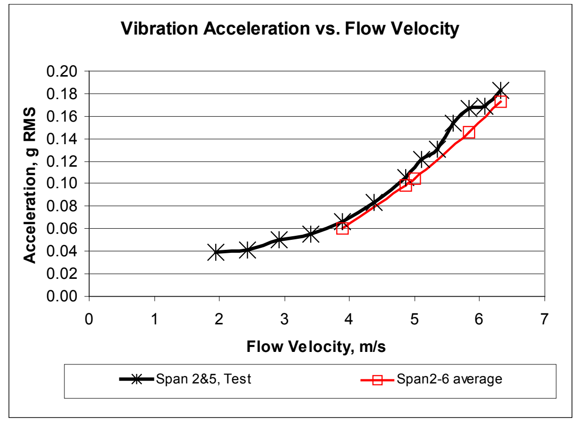

FIGURE 5: ACCELERATION AMPLITUDE VS. FLOW VELOCITY COMPARISON

3.2 FUEL ROD FRETTING WEAR TEST SIMULATION

Westinghouse has performed many endurance tests to evaluate fuel fretting wear performance in the VIPER (Vibration Investigation & Pressure-drop Experimental Research) loop located in Columbia, South Carolina, USA. The VIPER Loop can contain two full scale fuel assemblies.

VIPER tests are mainly used to compare any new design with a benchmark design, which has extensive field experience. After VIPER test, all fuel rods are carefully examined to identify wear scars. Each identified wear scar is measured by a 3-D laser scan to obtain wear depth and wear volume.

Simulating a VIPER test is a very difficult task due to uncertain interactions of a fuel rod and its supports. To overcome uncertainty, the VITRAN code uses its Monte Carlo function to generate a large number of single rod models (100 individual models in a normal simulation) with random support conditions based on the defined distribution and the parameters. The main goal of VITRAN simulation is to get statistic similarity with VIPER test data due to the stochastic nature of flow induced vibration, support condition and fretting wear.

VITRAN calculates the rod displacements and impact forces against the supports by numerically integrating the rod motion. The code numerically calculates time-averaged values for the normal work rates on support of grids, the volumetric wear rates and wear depths during the wear process.

One of the VIPER test comparison parameter, Average Grid Wear Scar Depth (GSD), is a measure of the average wear scar depth per grid elevation. GSD is very often used to show test data intuitively.

Figure 6 gives the comparison of the distribution of wear along grids. Again, VITRAN and VIPER show good agreement overall. The wear at Grid 2 seems not to agree well and VITRAN results show more wear. This may be because that

VITRAN PSD excitation force at Span 1 is higher than it should be. Since lacking FACTS data at Span 1, it is not modeled well in FACTS simulation.

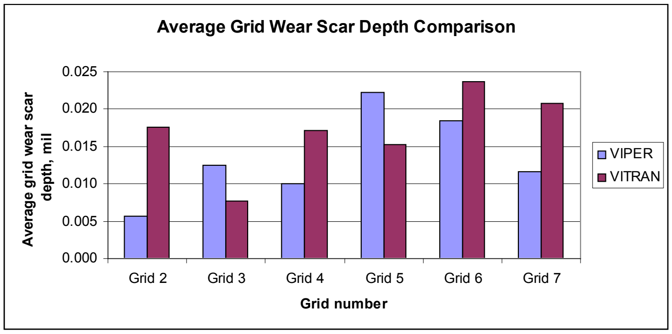

FIGURE 6: AVERAGE GRID WEAR SCAR DEPTH (GSD) COMPARISON

3.3 FUEL ROD VIBRATION INDUCED BY COOLANT PUMP BLADE PASSING PULSATION

During normal reactor operation, Reactor Coolant System (RCS) pump blades generate acoustic pressure pulsations inside reactor core at the harmonic frequencies of blade passing.

Direct pressure transducer measurement inside the reactor pressure vessel shows there is a significant pressure peak at the pump first blade passing frequency, 100 Hz, a reactor [4] (see Figure 7).

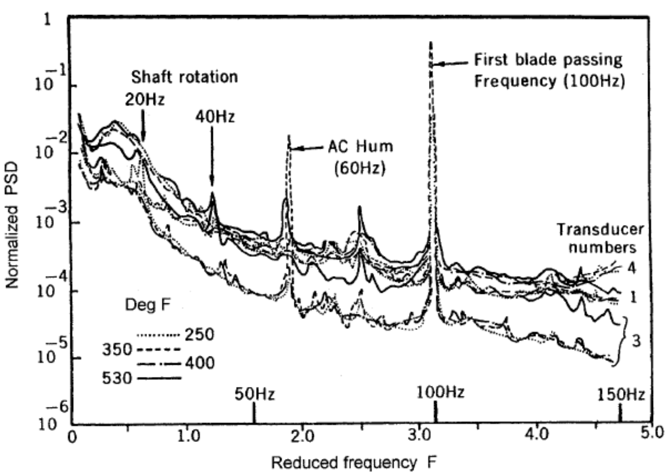

FIGURE 7: PRESSURE FLUCTUATIONS IN SIDE A NUCLEAR REACTOR MEASURE BY A DYNAMICS PRESSURE TRANSDUCER [3]

It is common knowledge when an excitation force frequency matches structure natural frequencies, resonance occurs and a very small force can cause significant vibration. If resonance occurs in a mechanical system it can be very harmful – leading to eventual failure of the system.

For PWR reactor plants, the pump rotation speed and the number of blades are different, which results in different first blade passing frequency (BPF), expressed as Equation (1).

First (BPF) = Pump RPM/60 * Number of Blades

For PWR fuel designs, the fuel rod natural frequencies are different due to rod support span lengths and rod diameters. A fuel rod has multiple spans and support conditions are also varied in the operation life. Therefore, natural frequency of the rod first mode is approximately calculated in a range.

Figure 8 and Figure 9 show BPF and fuel rod first modal frequency of two different types of plants, Plant A and Plant B, respectively. A same fuel assembly design was loaded for both types of plants for many cycles with extensive fuel performance experience. Plant A has no GTRF issues since the BPF is higher than the rod first modal frequency (Figure 8). Plant B always has significant GTRF issues since the BPF is overlapped with the rod first modal frequency (Figure 9).

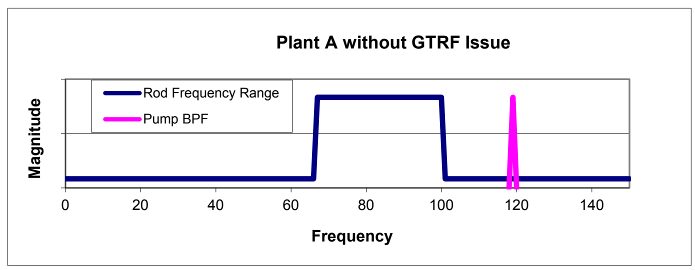

FIGURE 8: ROD FIRST MODAL FREQUENCY RANGE AND BPF of Plant A

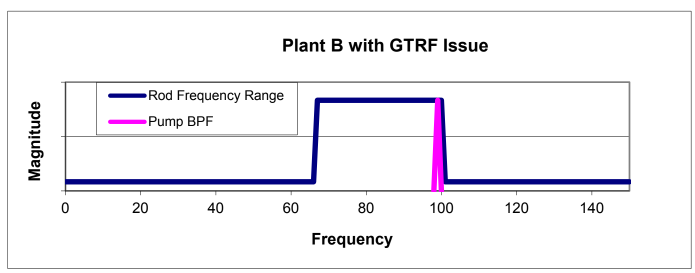

FIGURE 9: ROD FIRST MODAL FREQUENCY RANGE AND BPF of Plant B

To investigate GTRF issue and demonstrate BPF pulsation effect, the fuel rod vibrations in full scale fuel assembly are measured in VIPER hydraulic loop with variable speed pump. First BPF pulses can be easily identified by pressure transducers mounted on flow housing wall and accelerometers mounted on pumps and flow housing. By measuring rod vibration amplitudes and FFT (Fast Fourier Transform) spectrum, the rod high vibration and resonant vibration can be observed.

To simulate this BPF pulsation effect, VITRAN fuel rod model has both turbulent random force and sinusoidal lump force as excitation force at each spans.

Figure 10 and Figure 11 show the acceleration FFT and PSD plots of rod vibration from test measurement and VITRAN simulation, respectively. The pump pulsation effects on rod vibration spectrum can be seen obviously in both plots.

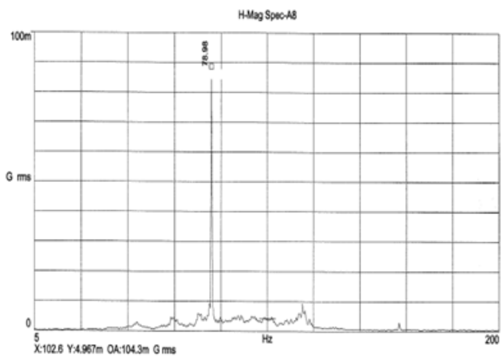

FIGURE 10: ACCELERATION FFT OF AN INSTRUMENTED FUEL ROD FROM TEST

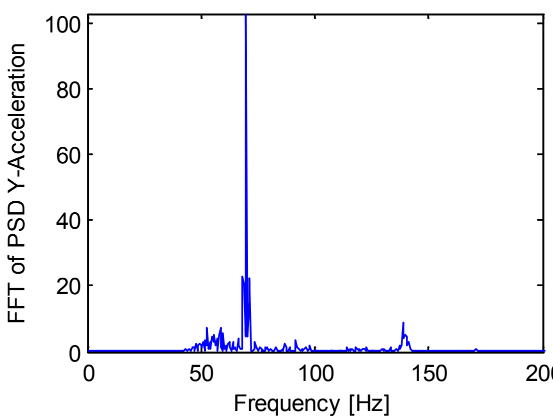

FIGURE 11: ACCELERATION FFT OF AN FUEL ROD FROM VITRAN SIMULATION

By varying the BPF, VITRAN simulation results show that vibration amplitudes and work rate significantly increases when pump pulse frequency matches to the rod natural frequency. For this case, the workrate is increased by 2 ~ 3 times. VITRAN simulation results demonstrate the principle of mechanical vibration. Acoustic pressure pulsations generated by reactor coolant pump blades are believed to be one of the factors to cause fuel leaking in some reactors.

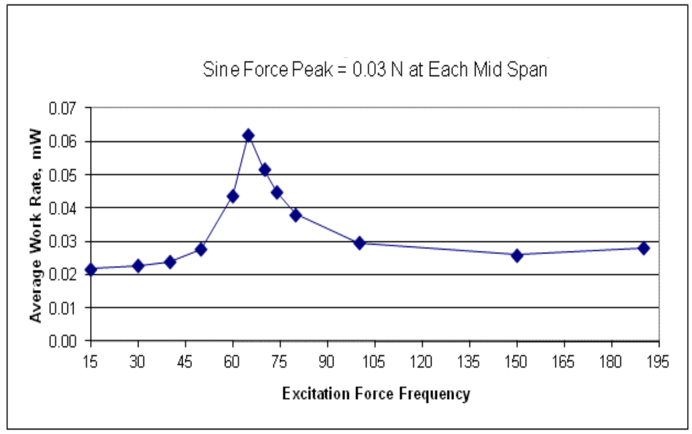

FIGURE 12: WORKRATE VARIATION WITH BPF

4. CONCLUSIONS

VITRAN integrates hydraulic, nonlinear structural and tribological effects. The code is calibrated with test data and can reasonably predict GTRF performance in a reactor. The code has been used to successful to help to identify GTRF root causes in serval applications.

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