Issues on Flow-induced Vibrations in Nuclear Fuel Assemblies and Structural Components of Nuclear Power Plants

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1. Introduction

Nuclear power plant is a complex thermo-fluidic-mechanical system where single-phase water discharged from a Reactor Coolant Pump (RCP) absorbs enormous heat generated by nuclear fission in the reactor core, converts water into dry steam in the Steam Generator (SG), and ultimately produces electricity in the turbine. Flowing water and steam physically affect surrounding structures. The phenomenon is called flow-induced vibration (FIV), and more broadly speaking, fluid-structure interaction (FSI). In the fluid system, structures may become unstable under certain flow velocity, or experience resonance when the natural frequency of the structure is near periodicity in flow. Those are the two most dangerous mechanisms that are destroying the structure within a short period of time. At the lower flow velocity than this, generally the structure may experience wear damage due to small vibrations over a long period of time. This is the so-called the wear due to random turbulence excitation.

In the PWR reactor, the barrel just inside a vessel holds up significantly important structures such as fuel assemblies, control rods, baffles, upper and lower core support plates and control rod drive mechanism. The structures in the reactor respond to acoustic frequencies in coolant flow generated by the rotation of the shaft of RCP that is a far-field noise in reactor core.

The barrel is subjected to axial flow in narrow gap between the vessel and the outer wall of the barrel. The narrow gap give strong effects to neighbor structures. An added-fluid mass may become enormous, sometime more than the structure mass, which has to do with how narrow the gap is.

In the reactor core, there are more than hundreds of thousands of nuclear fuel rods subjected to strong axial flow. The fuel rods are supposed to vibrate by random turbulence excitation force in axial flow.

likewise, control rods that are moving along the guide tubes within the fuel assembly are subjected to a narrow-axial-flow-induced vibrations.

In this paper, cross-flow-induced vibrations as well as axial-flow-indued vibrations have been discussed in structures inside PWR core and research reactor core and outside of the reactor core such as a SG and spent fuel storage pool.

2. Mechanisms

In this section, basic FIV mechanisms are presented and explained for important structural components in nuclear power plants and research reactor.

2.1 Flow induced vibrations of fuel assembly

The problem of the PWR FR is not on fluidelastic instability that causes excessive vibration and failure in short time but on turbulence-induced excitation that generates small amplitude and may cause long-term fretting-wear damage. The fretting wear by this sub-critical vibration is generally accepted as a root cause of a fuel rod failure which is not known well yet. Since the FIV obviously generates the relative motion between the FR and spacer grid, that can lead to fretting damage of the FR, it is very important to understand what is the actual vibration behavior of the fuel rod supported by spacer grids[1].

Plate-type fuel assemblies are utilized in many research reactors. Some are open-loop, pool-type reactors, but others are pressurized reactors with high coolant flow rates. Parallel flows between the fuel plates may make these plates unstable. Several studies in the early 60s reported that the plates could lose their stability through a static type of instability. In accordance with studies in the 70s, however, the type of instability, whether static or dynamic, may depend on the boundary conditions. It is generally accepted that a static-type of instability possibly occurs in fuel plates subjected to a narrow-axial flow between several different fuel plates [2].

2.2 Flow-induced vibrations of SG heat exchanger tube

Two-phase cross flow exists in many shell-and tube heat exchangers such as condensers, evaporators and nuclear steam generators. There are several flow-induced vibration excitation mechanisms, such as fluidelastic instability, periodic wake shedding resonance, turbulence-induced excitation and acoustic resonance, which could cause excessive vibration in shell-and tube heat exchanges. Of cause, fluidelastic instability is by far the most important. Excessive vibration due to fluidelastic instability often leads to tube failures within a short period of time in the heat exchangers. Fig. 1. shows three basic mechanisms as flow velocity increases such as a Random Turbulence Excitation (RTE), a resonance with vortex shedding frequency and a fluidelastic instability in very high flow.

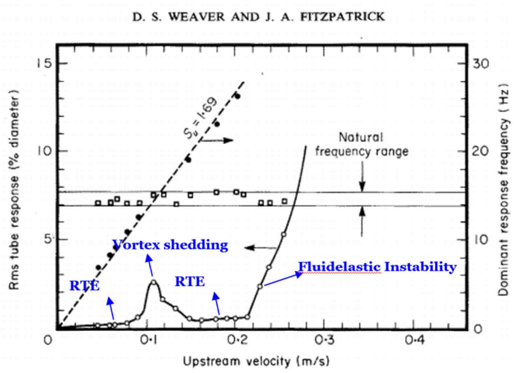

Fig.1. Amplitude and frequency response of SG heat exchanger tube as flow velocity increases[Weaver and Fitzpatric, 1988].

2.3 Sloshing

When a water-filled Spent Fuel Storage Pool (SFSP) is subjected to dynamic excitation by an earthquake, hydrodynamic forces arise by water oscillation (called sloshing) in the storage pool. It has been reported that, at times, such hydrodynamic forces cause severe permanent damage to the wall structures of the storage pool [3]. In addition to structural damage, when severe sloshing occurs in the SFSP of an NPP, coolant contaminated by radioactivity could flow over the wall of the SFSP. When designing an SFSP in regards to seismic incidents, several issues must be considered. These include such as overflows of contaminated water, the structural integrity of the spent-fuel assemblies and spent-fuel storage racks, and the damage that might result from impacts between racks, as well as between racks and the walls of the SFSP.

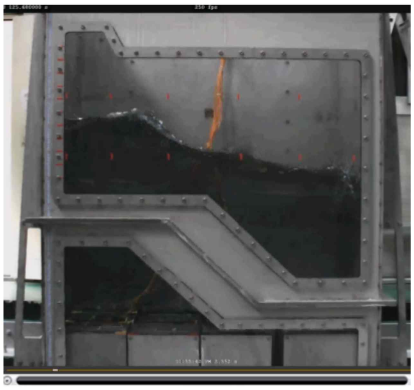

Fig. 2. Sloshing simulation tests on a small model of SFSP

3. Discussions

In this paper, Flow-induced vibration or fluid-structure interaction are presented in commercial nuclear power plants and a small research reactor. In reactor core, fuel assembly and reactor internal structures are mostly subjected to axial-flow-induced vibrations, especially within the narrow gaps. it is well known that the fluid-structure interactions in the narrow gap are much stronger than in broad fluid boundary.

In SG, unlikely, vibrations become worsen due to a cross-flow-induced vibrations. This vibration phenomenon gets much harder to understand the physics due to two-phase flow. It is well known that SONGS nuclear power plants stopped commercial operations because of fluidelastic instability in SG.

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