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HYDRODYNAMICS AND STRUCTURAL MECHANICS OF JET PUMPS IN A BOILING WATER REACTOR: CFD ANALYSIS

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ABSTRACT

The aim of this work is to the failure of jet pump analysis using the hydrodynamics and structural analysis coupling in a typical BWR. Different structural problems in jet pups of Boiling Water reactors (BWR) have been reported in the last 20 years. The liquid in the jet pump is accelerated due to high differential pressure in the nozzle that induces vibrations in the slip joint of the diffuser. If the vibrations are out of the range of the natural frequency, they may produce a leakage in the slip joint or a rupture in the riser pipe. A leakage in the area of the slip joint of 5% is simulated to estimate the frequency of vibration of the jet pumps. The results show that as the frequency of the vibration increases the displacement of the jet pump and the stress increases and frequencies higher than 47.5 Hz exceed the modulus of the elasticity limit of the material.

Keywords: Jet pumps, boiling water reactor, slip joint, hydrodynamics, structural mechanic.

INTRODUCTION

In Bulletin80-07 (USNRC, 1980a) the USNRC reported the failure of the jet pump No 13 in Dresden Unit 3 on February 2, 1980, in coast-down condition to refueling shutdown. The plant parameters changes reported were: decrease of generator electrical output, core thermal power decreased, total core flow increased, core plate differential pressure decreased, B recirculation loop flow increased and A recirculation loop flow remained. These changes were observed in the control room by the reactor operators and were identified as jet pump failures. Individual jet pump readings were taken and the failure of jet pump No.13 was identified. Visual inspections of the jet pumps and vessel annulus revealed the hold-down beam assembly of the suspect jet pump had broken across its ligament sections at the mean diameter of the bolt thread area. Ultrasonic examination of all jet pumps showed indications and cracking of 6 to 20 mils for some jet pumps. On March 1980, during the shutdown for refueling, an ultrasonic examination was performed on all 20jet pump hold-down beam assemblies at Quad Cities 2, and one beam crack indication in the same location as found in Dresden was observed. In the same year, Pilgrim Unit 1 announced a crack indication in three beams after the ultrasonic examination of all jet pumps. A similar crack was also notified of a hold-down beam at a foreign BWR facility.

General Electric said that during the experience at Dresden Unit 3, Quad Cities Unit 2, and Pilgrim Unit 1, the concern arises that the hold-down beam assemblies and subsequent jet pump function may degrade significantly during operation. This potential for degradation could lead to jet pump disassembly and possibly reduce the margin of safety during postulated accidents (USNRC, 1980b)

In December of 1993, the USNRC issued the Information Notice No. 93-101 (USNRC, 1993): Jet Pump Hold-Down Beam Failure, to alert all holders of operating licenses or construction permits for BWRs regarding the jet pump hold-down beam failure described in the Bulletin 80-07 (USNRC, 1980a), to review the information for applicability to their BWRs and consider actions to avoid similar problems. In this Information Notice, there is a description of an event in Grand Golf when the High Core Spray System operates due to a signal of low water level in the reactor vessel that derived in a reactor. The oscillation in the water lever was detected by the instrumentation due to a displacement of the jet pump mixer No 10 that separated from the diffuser and relocated between jet pumps 8 and 9. The hold-down beam for jet pump 10 had cracked and failed. The failed beam showed a crack face-covering more than 270° of the cross-sections, GE concluded that the probable cause of the failure was an intergranular stress corrosion crack that propagated over 80 percent of the fracture surface. However, fatigue covered the remaining 20 percent of the surface.

A finite element model to study turbulence at the connection between the recirculation pump impulsion piping and the manifold was developed by Moreno (2009). He found that poor hydraulic design of the manifold produced bistable flow causing noise and turbulences leading to vibrations, power fluctuations, (possible) core instabilities, pressure, and/or coolant density changes, among others, he concluded that to reduce turbulence and balance flows in the jet pumps two things were needed: the restriction at the central feed had to be increased and reduce the rest, and the manifold diameter had to be increased. This bistable flow phenomenon has been studied and it has been reported to have repercussions on jet pumps (Nuñez-Carrera *et al.,* 2009; Moreno, 2011).

An analytical and experimental study of a cylindrical rod vibrating in a viscous fluid enclosed by a rigid, concentric cylindrical shell was performed by Chen *et al.* (1976), to understand the phenomenological mechanisms. On the other hand, the evaluation of the structural integrity of the jet pump assembly of a BWR with a CFD method is one of the best options in the absence of complete experimental data. Ten modes of vibrations and their natural frequency were calculated by Stevens *et al.* (2000). The main conclusion was that in these conditions, fatigue loads may be developed and cause some damage.

In this work, a three-dimensional analysis with a computational fluid dynamics methodology is presented. For the model verification, the results of nine natural frequencies are compared with the work of Stevens *et al.* (2000). Then, the jet pump failure using the coupling of the hydrodynamics and the structural analysis in a typical BWR is discussed due to leakage in the slip joint.

RECIRCULATION SYSTEM DESCRIPTION

The Recirculation System (RS) of a Boiling Water Reactor (BWR) consists of two recirculation loops. The function of the RS is to sweep the void located in the core of the reactor to increase fissions and therefore thermal power. The RS is an alternative way to control the power of the reactor. Each loop consists of:

- A recirculation pump is driven by a variable speed motor.
- 10 jet pumps.
- Valves, piping, and instrumentation.

The pumps are installed in the annular region between the core barrel outside of the reactor vessel (Figure-1). The driving head for these jet pumps is provided by the pressure head on the discharge of the recirculation pumps. The jet pumps are located inside the reactor vessel annulus, between the core shroud and vessel wall, depicted in Figure-2. The recirculation pumps are located in the dry well of the containment, offside of the reactor vessel. Each recirculation pump discharges into five risers. Each riser, in turn, penetrates the vessel and supplies the driving flow for two jet pumps. Water from the moisture separators, steam dryers, and the feed water system returns to the annulus area forming the suction for both, the jet pumps and the recirculation pumps (drive flow). The mixture of water enters the reactor vessel's bottom head and is circulated through the core.

The recirculation pump speed can be modified from about 30% up to about 102%. The pumps are located below the reactor vessel to satisfy Net Positive Suction Head (NPSH) requirements.

According to General Electric if both recirculation pumps are operated with a high flow difference between the two loops can cause flow reversal or oscillation in the low-flow loop (GE, 1973). Flow reversal or oscillation can result in vibration of the jet pumps and riser braces, thus, an increase of fatigue in the mechanical components. To minimize vibration, the recirculation pump speeds shall be within 5% of each other when the core flow is equal to or greater than 70% of rated and within 10% when less than 70% as required per Technical specifications (TS). During the idle pump startup with the other pump in operation, it is also necessary to reduce the operating pump's speed to less than 50% before starting a pump to reduce or minimize these effects.

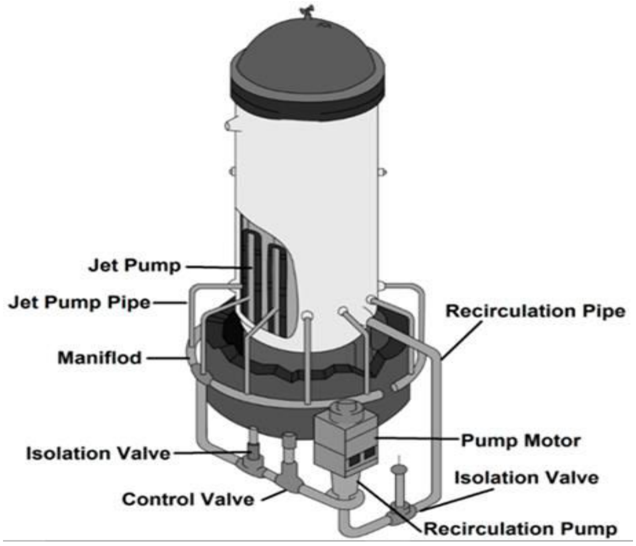

Figure-1. Recirculation system of a Boiling Water Reactor (GE, 1973).

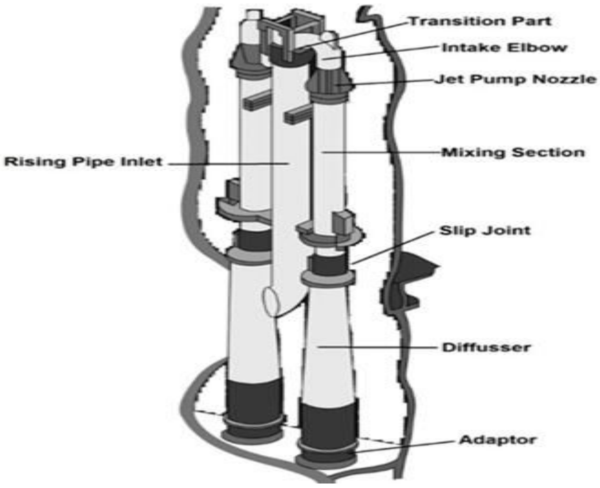

Figure-2. Typical assembly of a jet pump of a Boiling Water Reactor (Based on Kudirka and Gluntz, 1974).

JET PUMPS DESCRIPTION

The jet pump is a simple device for controlling entrainment and discharge fluids (Yamazaki *et al.,* 2007). In general, it consists of a driving nozzle, a suction inlet, and a diffusor (Figure-3). Typical dimensions of the jet pump assembly of a BWR/5 are: A=0.397m, B=0.273m, C=0.196m, D=1.600m, E=5.731m, F=0.160, G=3.473m and H=0.502m (Kudirka and Gluntz, 1974). The jet pump assembly of a typical BWR corresponds to a second-generation used in a BWR/5.

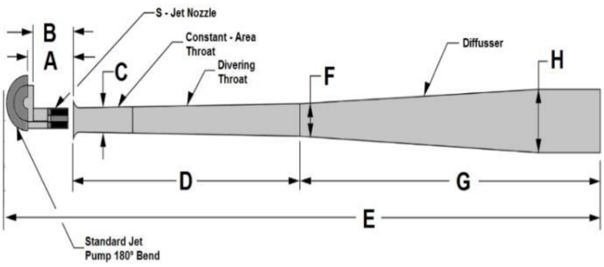

Figure-3. Jet pump outline (Based on Kudirka and Gluntz, 1974).

Special emphasis is placed on the slip joint (Figure-4) due that in the operation experience it has been reported leakage trough this component (Inada, 2015; Mulcahy, 1983).

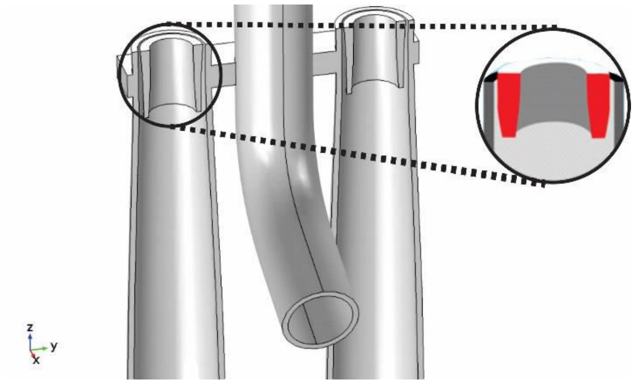

Figure-4. Slip joint in the diffuser of the jet pump.

JET PUMP MODEL

The 3-Dimensional jet pump model is illustrated in Figure-5. The main assumptions are that the recirculation pump, the manifolds, and the feed water piping are not considered. The initial conditions of pressure and temperature correspond to 100% of the power. The hydrodynamics and structural mechanics of jet pumps were obtained using COMSOL Multiphysics®. For this analysis, a total of 113377 nodes were considered, obtained after an invariability analysis of the mesh size, i.e., invariability of the results with respect to the node number.

The Flow Induced Vibration (FIV) is a function of flow velocity and results from the turbulence mixing boundary layer and pressure pulsations in pipes, tees, and reducers, resulting in shaking forces (vibrations) with low frequency (<100 Hz). These vibrations increase the stress and fatigue in the piping systems, hereunder a vibrations study of the jet pumps at different natural frequencies is analyzed.

The vibration of a whole body can be described completely as a combination of individual movements of six different types. These are translations in the three orthogonal or normal directions, *x*, *y*, and *z*, and rotations around the same axes. Any complex movement in the body can be obtained through combinations of those six movements. Therefore, a body has six degrees of freedom.

The pressure field model introduced by Corcos (1963) is used to analyze the vibration induced by the axial flow in the jet pumps:

$$\psi_{pp}\left(\omega, z_1, z_2, \theta_1, \theta_2\right) = \phi_{pp}\left(\omega\right) A\left(\frac{\omega\left|z_2 - z_1\right|}{v_c}\right) \times B\left(\frac{\omega D\left|\theta_2 - \theta_1\right|}{2v_c}\right) \times \exp\left(i\omega\frac{\omega\left|z_2 - z_1\right|}{v_c}\right) \tag{1}$$

where ψ_{pp} is the cross-spectral density of the pressure field, ϕ_{pp} is the pressure power spectrum at a specific point, ω is the angular frequency, v_c is the convection speed, $|z_2 - z_1|$ is the size of the axial segment, $|\theta_2 - \theta_1|$ is the angular difference, in this particular case, the diameter of the cylinder. Now, *A* and *B* are spatial functions determined by the material, geometry, and dimensions of the object analyzed, as a first approximation in this study they are considered equal to one (Noureddine and Sgard, 2017).

Figure-5. Jet pump representative used for hydrodynamics and structural mechanics analysis and its domain elements.

The pressure power spectrum is calculated according to (Moreno, 2010):

$$\phi_{pp}\left(f_r\right) = \begin{cases} \dfrac{0.272 \times 10^{-5}}{f_r^{0.25}}, & \text{for} \quad f_r < 5 \\ \dfrac{27.75 \times 10^{-5}}{f_r^{3}}, & \text{for} \quad f_r > 5 \end{cases} \tag{2}$$

where f_r is the reduced frequency, that is given by:

$$f_r = \frac{D_h f}{v} = \frac{\omega D_h}{2\pi v} \tag{3}$$

where f is the frequency, v is the speed, D_h is the hydraulic diameter. The convection speed of the limit layer is given by:

$$v_c = v\left[0.6 + 0.4\exp\left(-2.2\frac{\omega\delta}{v}\right)\right] \tag{4}$$

Where

$$\delta = \frac{D_h}{2(n+1)} \tag{5}$$

with

$$n = 0.125m^3 - 0.181m^2 + 0.625m + 5.851 \tag{6}$$

Where

$$m = \log(\mathrm{Re}) - 3 \tag{7}$$

the amplitude of the vibration is given by:

$$y_{rms} = \begin{cases} v^{1.5}, & \text{if} \quad fr < 0.2 \\ v^2, & \text{if} \quad 0.2 < fr < 3.5 \\ v^3, & \text{if} \quad 3.5 < fr \end{cases} \tag{8}$$

According to Moreno (2010), these equations result in the generation of transversal forces, which move the mixer parts, the elbows, and the riser provoking damage as a result of the stress, and therefore breaks are highly probable.

The fluid-structure interaction is carried out in 3D for this analysis. To simulate external forces and fix boundary conditions, the structure is introduced into a control volume at a steady state. Figure-6 shows the points used to obtain the boundary conditions to simulate fluid-structure interaction.

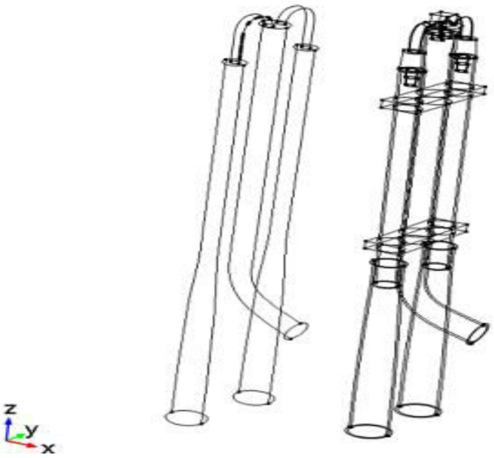

Figure-6. Points used to obtain the boundary conditions for fluid-structure interaction.

RESULTS

For the model verification, the results of the structural frequencies in the jet pump were compared in Table-1 with those obtained in previous work (Stevens *et al.,* 2000). Nine modes of vibrations and their natural frequencies were calculated. In this table, it can be observed that the natural frequency obtained in this work is similar with respect to the previous study, in which they applied different computer fluid dynamics, and the differences may be due to geometry, materials, and boundary conditions. The sixth mode exceeds the modulus of elasticity limit for 350 stainless steel which is approximately 190 GPa - 210 GPa.

Then, different leakages in the slip joint were simulated to estimate the deformation due to flow-induced vibrations. Figure-7 shows the turbulent flow that hit the inner face of the diffuser pipe due to the leakage of 5% in the slip joint.

Figure-8 shows the fluid speed in the jet pump diffuser. At the top, the speed is greater than 340 m/s, while at the bottom the speed is approximately 55 m/s.

Figure-9 shows the displacement, from the original position of the jet pump, due to flow-induced vibrations at a frequency of 34.2 Hz. The maximum displacement is approximately 3 m, which is at the top of the jet pump.

Table-1. Structural frequencies.

Mode	Frequency (Hz)	
	Stevens *et al.* (2000)	This work
1	27.9	21.8
2	30.7	30.6
3	34.6	34.2
4	35.5	37.6
5	44.6	39.8
6	47.5	46.5
7	53.9	59.3
8	54.4	64.2
9	57.7	72.5

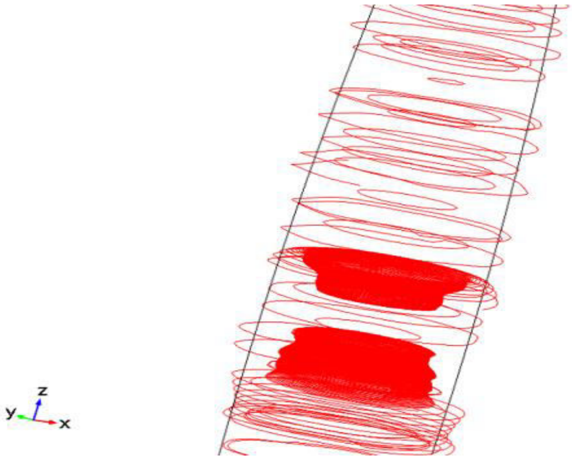

Figure-7. Turbulent flow in the diffuser pipe due to the leakage of 5% in the slip joint.

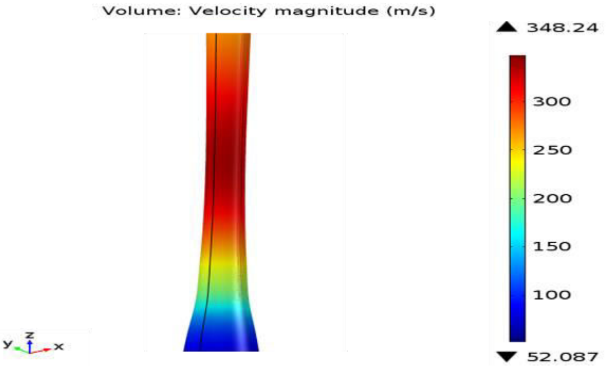

Figure-8. Fluid speed in the diffuser of the jet pump.

Figure-10 shows the effect of flow-induced vibrations with a frequency of 46.51 Hz, it can be observed on the left side of the figure is the displacement and deformation of the jet pump where the stress on the jet pump is greater than 2×10^{11} N/m^2 in some regions.

As shown in Figures 9 and 10, when the frequency increases, the displacement of the jet pump increases causing material deformation.

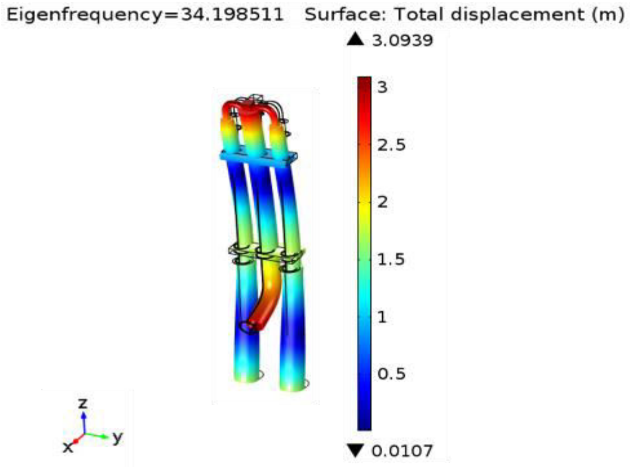

Figure-9. Displacement, from the original position of the jet pump, due to flow induced vibrations at 34.2 Hz.

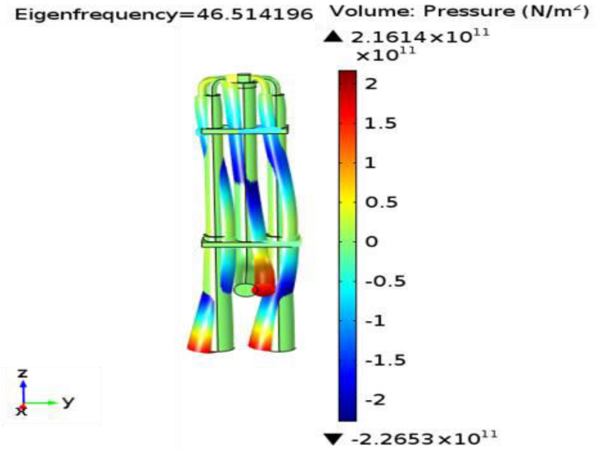

Figure-10. Displacement and stress in the jet pump due to flow induced vibrations at 46.51 Hz.

CONCLUSIONS

The first vibration modes presented have natural frequencies below a value of approximately 47.5 Hz. The stresses increase as the frequency of the flow-induced vibration increases. The sixth mode, reported previously, exceeds the modulus of elasticity limit of the material (for 350 stainless steel is approximately 190GPa - 210 GPa). When exceeding this limit, the structure of the jet pump, just where it is connected around the slip-joint undergoes deformation to such a degree that it is impossible to return to its original shape and finally it can lead to a breakdown. Future work consists of the analysis of transients during the failure of a jet pump.

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