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FSI IMPACT INVESTIGATION OF STEAM LINE BRANCH HANGER FAILURE

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ABSTRACT

In a multi unit nuclear power station, repeated hanger failures were observed in the steam condenser reject lines, at the same location in the piping run, in various operating units. The mode of failure appeared to be a shear fracture of the threaded end of one of the rods in the trapeze hanger. The hanger is located in the piping run in the vicinity of a reducer and an elbow where the stream flow changes direction. Although a condensed steam water slug impact causing the hanger failure is a possibility, yet it is believed that structural resonance is responsible for the hanger failure and the source of the resonance forcing function is from the steam flow induced pipe vibrations. The coupling of fluid motion and the hanger structural response leads to this undesired outcome.

This paper will investigate the nature of fluid motion in the pipe which is driven by high mass flow rate, pressure drop through a reducer and flow discontinuity resulting from the presence of an elbow. The magnitude of the steam flow induced vibrations and resulting impact forces at the elbow and their frequency of occurrence will be computed. The transient piping vibrations amplitude and their frequencies will be calculated and compared with the natural frequency of the trapeze hanger for presence of flow induced structural resonance as a possible mode of hanger failure.

INTRODUCTION

The steam reject system is essential to the safety of the steam supply system in CANDU Pressurized Heavy Water Reactor nuclear power plants (PHWR). A typical CANDU unit has one or more steam generators with feed water supply. During normal operation, the generated steam is delivered to turbines. There are two separate steam condenser discharge piping sections connected between the steam balance header and the steam condensers, comprising part of the Steam Reject System. When the turbine is tripped due to an emergency outage or is operating at a lower load, approximately 60% of full reactor power steam output may be diverted through Condenser Steam Discharge Valves (CDSVs) to the condensers via the steam reject system and keep the reactor operating for an extended basis, up to 90 hours. This arrangement allows operation for extended periods at low turbine loads, allowing the unit to return quickly to 100% full load operation without much variation in the reactor activity, Kok (2016).

Steam reject system piping consists of two 24″ lines, one on the north side and the other on the south side of the condenser. Each of the 24” lines branch off into three 18″ lines, supplying steam to each condenser shell. Steam, flowing through the 18″ line, passes through a manual isolating valve, the CSDVs and enters the condenser through condenser shell inlet nozzle. The steam reject system would normally operate when the turbine undergoes a load rejection, turbine trip, or is suddenly unloaded via the electrohydraulic governor. The steam reject system provides a means for fast and continuous rejection of up to 60 percent of the turbine steam flow that allows the reactor to continue producing power at a level which will not cause a shutdown. Consequently, this system is considered as a “poison prevent” system.

The CSDVs are pressure reducing valves and they are capable of opening from fully closed to the full flow position within 2 seconds. Steam reject line piping is manufactured from Schedule 40 stainless steel pipes. The steam reject piping is code classified as Class 6 (non-nuclear) as per the guidelines of Canadian standard CSA N285.0 (2008).

PROBLEM DEFINITION

Vibration of the steam reject line in a multi unit pressurised heavy water nuclear power plant has recently caused repeated failures in pipe hangers and supports. One of the impacted hangers lies on the 18” line in between a 24”×18” reducer and the elbow of pipe section which sends steam to condenser via the isolation valve and the CSDV. The pressure drop caused by the reducer and a change of flow direction by the piping elbow is believed to produce flow instability leading to vibration of pipe hanger. The pipe hanger is a trapeze spring hanger which is made of ¾” steel rods. One of the hanger rods sheared completely at its threaded portion underneath the base of the hanger. It is believed that the main mechanisms that would cause this vibration induced failure, is the coupling between dynamic flow instabilities in the main steam reject line with one of its structural vibration modes. If the frequencies of the flow instabilities match the resonant frequency (frequencies) of the piping hanger and support system, a dangerous condition may arise leading to support failure. Therefore, the main objective of this paper is to determine whether flow-induced vibration is a plausible source of the steam reject line vibration or not and whether it contributed to the multiple failures of hangers on the steam reject line.

HANGER FAILURE INVESTIGATION METHODOLOGY

The hanger failure investigation will involve the calculation of pressure and flow variation within the steam reject line. The estimated forces induced from fluid motion will be used to estimate the piping transient response. The piping natural frequencies will help understand the nature of piping response. Frequency response will be estimated from the piping displacement time histories. Finally, the piping response frequencies will be compared with hanger natural frequencies for presence of resonance. The following analytical steps will be carried out.

a. Computational Fluid Dynamic analyses
    a1. All three CDSVs open in two seconds (normal operation)
    a2. One CSDV is stuck closed while other two open in two seconds (abnormal operation)
b. Steam reject piping modal analysis
c. Fluid Structure Interaction coupled analysis.
d. Hanger natural modes analysis

ASSUMPTIONS AND SIMPLIFICATIONS

Following assumptions and simplifications were used in the fluid dynamic as well as structural analyses:

- Steam reject line is a very long system. To reduce numerical model size, only a small portion of the 24” and 18” lines, in the vicinity of the failed hanger, were used in the fluid dynamic and structural models.
- For the fluid dynamic analysis, mass flow inlet boundary condition at the piping inlet and pressure outlet boundary condition was considered at CSDVs exits.
- Only two limiting cases of CSDVs operation were considered, i.e., all three valves open and operation with one the CSDVs stuck closed.

- Linear elastic analysis without the use of contacts between interfacing surfaces was performed.
- The damping was not considered in the transient dynamic analyses to get upper bound piping structural response.
- CSDVs and isolation valves were modelled with reduced cross section area (10% reduction compared with pipe cross section area for CFD analyses
- CSDVs and isolating valve masses were not considered in the coupled transient dynamic analysis. It was considered to have no impact because of presence of supports near the failed hanger.

FLUID FLOW ANALYSES

A numerical simulation was carried out to investigate the effect of the abnormal operation of the upstream Condenser Steam Discharge Valve (CSDV). The simulation was used to compare the mass flow rates and the time histories of the fluid forces on the walls of the piping section where support failure was expected. A steady-state solution is first obtained to determine the flow rates in the piping branches to the condenser. The steady-state solution is obtained for the cases where all valves are fully open, and for the case when one of the valves fails to open. A transient case is run to determine the time-dependent forces acting upon the walls of the piping section where support failure was expected. The transient analysis includes two cases. In the first case, all valves open in their expected response time of two seconds. In the other case, the most upstream valve is assumed to stay stuck closed, and the two other valves are assumed to open regularly.

The model is analysed by numerically solving the incompressible Navier-Stokes equations iteratively on the ANSYS Fluent Package (2022). The working fluid properties, in Table 1, are set to simulate steam at the pressure of 4200 kPa and 255 ^{o}C. To facilitate solution convergence, steam is assumed to follow the ideal gas law rather than using steam compressibility, which is expected to overestimate the generation and propagation of pressure waves and thus, such selection is considered conservative, Shaaban et all. (2019).

Table 1: Steam properties used in fluid flow simulations

Property	Value
Viscosity	17.627×10^{-6} [kg/m.s]
Molecular Weight	28.967 [kg/kmol]
Heat capacity	4086.8 [J/kg.K]
Heat conductivity	0.051613 [W/m.K]
Compressibility model	Ideal gas

As the expected flow is highly turbulent, the standard k-ε model is used to simulate the turbulent dissipation of energy in the flow. In this model, the turbulent is modelled by solving two additional transfer equations, one for the turbulent kinetic energy k and the other is for the turbulent dissipation rate ε. The wall is treated by a standard wall function to correct the calculation of the shear stress and viscous forces rather than fully resolving the boundary layer. The inlet flow is assumed to have a turbulent intensity of 5% and a turbulence length scale of 0.01m, equivalent to $k = 37.5\ m^2/s^2$ and $\varepsilon = 2066\ m^2/s^3$.

The computational domain is shown in Figure 1. The domain includes the piping between supports that are to be used in the subsequent structural analysis. The upstream segment is connected to a suitable point on the 24” line and assumed to be the inlet point to the fluid analysis. The inlet total conditions are set at the operating pressure, temperature, and steam quality at the steam generators: 4274 kPa, 255.5 ^{o}C, and 99.75% quality, respectively. The upstream side of each CDSV is treated to be an outlet for the fluid analysis, as the pressure is specified based on the operation specifications of the valves, setting the pressure at 4138 kPa and enabling a driving pressure difference of 136 kPa across the piping segment.

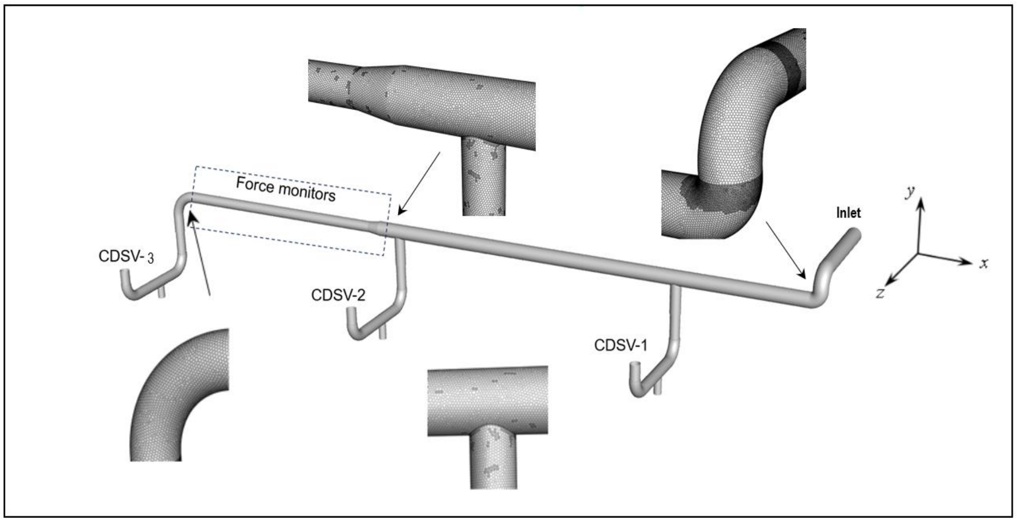


Figure 1. Computational domain for fluid flow calculations, showing selected mesh regions

The domain consists of 6.67×10^6 nodes representing 2.74×10^6 polyhedral cells. The number of nodes was tested to ensure mass flow rate results are not changed by more than 3% upon a mesh refinement. The boundary conditions are shown in Table 2. All pipe walls are modelled as ideal non-slip, adiabatic walls, and the heat loss through conduction is neglected. The force time histories are collected for 10 seconds and analysed to identify any dominant frequencies. The force time histories for up to 17 seconds are then used as an input to the subsequent structural analysis.

Table 2: Boundary conditions for steady-state and transient simulation cases

Case	Inlet	CDSV 1	CDSV 2	CDSV 3
Steady-State 1	P_{tot} = 4274 [kPa] T_{tot} = 255 [$^\circ C$] x = 99.75 %	P = 4138 [kPa]		
Steady-State 2		$\dot{m}$ = 0	P = 4138 [kPa]	
Transient		$\dot{m}$ = 0	for $t \leq 2$ [s]: $P = 4274 - 68t$ [kPa] for $t > 2$ [s]: $P = 4138$ [kPa]	

PIPING MODAL ANALYSIS

Piping modal analysis was required to study what impact, if any, the steam pressure pulsations had on the piping structural response when the CSDVs begin to open and also during the steady state operation of the steam reject line. The degree of amplification in response would depend upon the natural frequencies of the pressure oscillations and that of the steam reject piping. The geometry used in the fluid dynamic analysis was used to create an FEA model using pipe elements, ANSYS Workbench (2022) element type 288, along with restraints as per the piping design drawings. First fifteen modes were investigated.

FLUID STRUCTURE COUPLING ANALYSES

Before the CSDVs open, the steam reject line is full of pressurised steam. For the steam reject line hanger failure investigation, it is required to find out the piping response under all the active loads, i.e., the static dead weight, thermal expansion loads and the transient dynamic loads from steam flow. Time dependent forces obtained from fluid dynamic analysis would be used in a transient dynamic structural analysis and the dynamic analysis results will be added to superpose the static dead weight and thermal expansion load cases to get the complete piping transient response. The final step is to perform a Fourier transform analysis to find out the frequency content of the nodal displacements at the failed pipe hanger location.

The FEA model consists of 177 Pipe288 elements. They represent the 24”, 18” and 10” lines. The spring hangers are modelled with Combin14/Combin39 spring element types. The FEA model is shown in Figure 2 with the applied boundary conditions. The red arrows represent the time dependent forces obtained from fluid flow dynamic analysis.

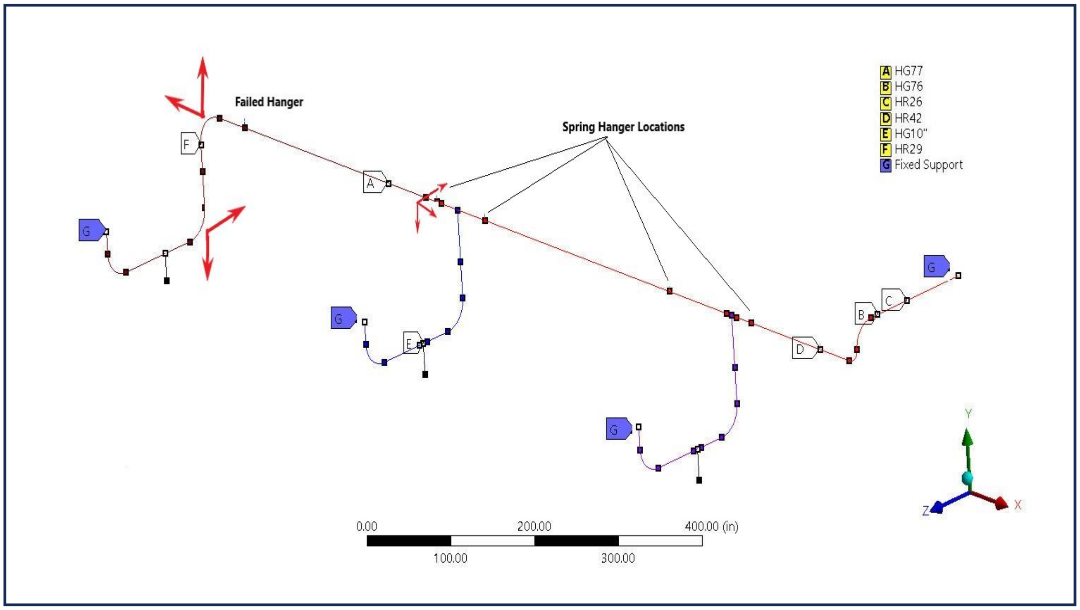


Figure 2. Steam reject line FEA model constructed with pipe elements

FAILED HANGER MODES AND FREQUENCIES

Finally, to know if the steam reject line hanger failed from the resonance from the fluid pressure pulsations, the dynamic characteristics of the failed hanger in the form of mode shapes and the associated frequencies needed to be calculated. The hanger was a trapeze hanger with steam reject line resting on it. The hanger sides are constructed from the ¾” rod roughly 10 feet long each. The base is constructed from two C-Channel 4×2 beams joined together. The spring cans are modelled as 30 lbs mass elements. The hanger rods are supported at the top via a pin connection.

DISCUSSION OF RESULTS

CFD Analyses Results

The mass flow rates in the steady-state cases are shown in Table 3. The steady-state flow velocity contours, shown in Figure 3 indicate a significant effect of the valve configuration on the flow rates and flow patterns.

The first 90-degree elbow upstream from CDSV1 has significant circulation due to the change in direction, and the maximum velocity is observed at the inner corner of the elbow. Notably, the closed branch in each leg had recirculating flow contributing to the pressure losses. The closure of one valve resulted in a reduction of the flow rate by 21% on average.

Table 3: Inlet steady-state steam mass flow rates

Case	**Valve Closed**	**flow rates [kg/s]**
Steady-State 1	None	Inlet: 525.4 kg/s CDSV 1: 130.9 CDSV 2: 172.1 CDSV 3: 222.4
Steady-State 2	CDSV 1	Inlet: 413.0 CDSV 1: 0.0 CDSV 2: 179.6 CDSV 3: 233.4

Flow velocity profiles are shown below:

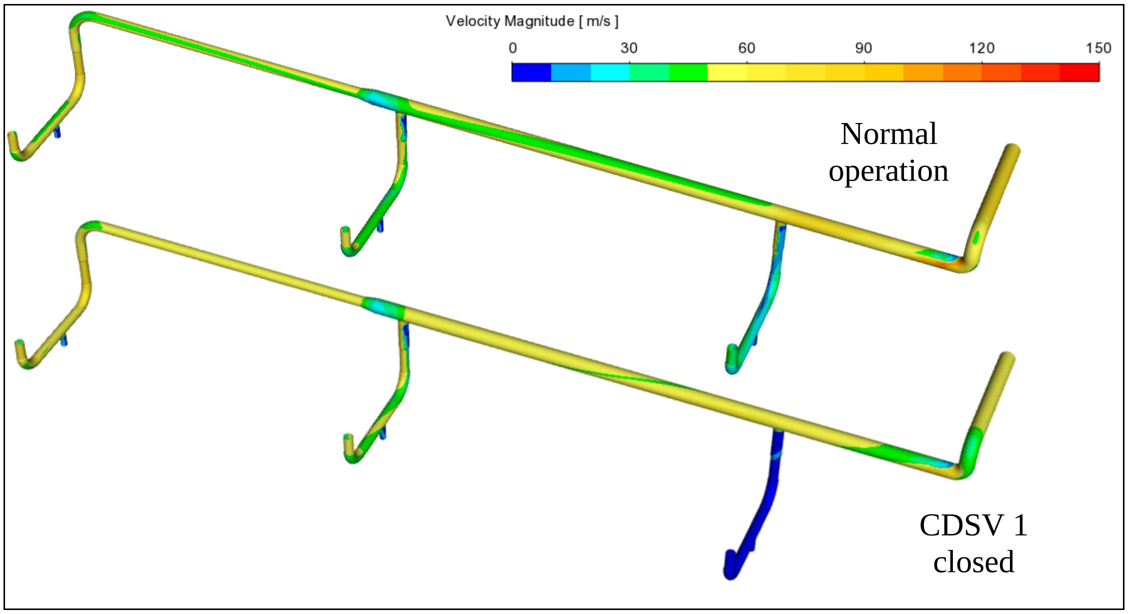
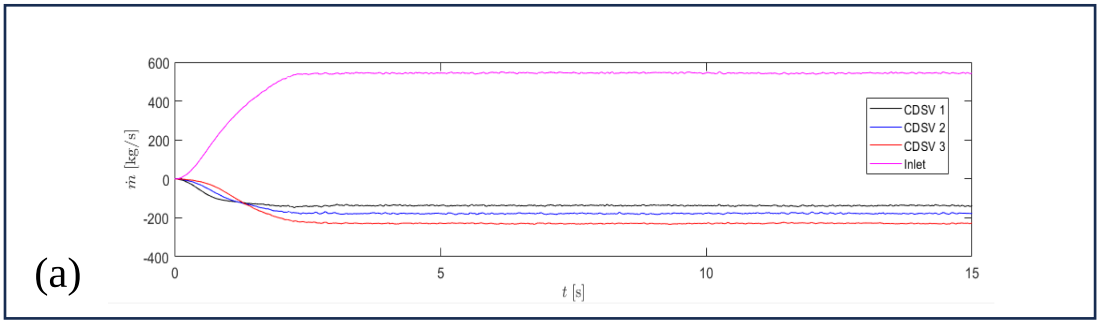


Figure 3. Contours of steady-state flow velocity magnitude at 10 cm from the pipe wall



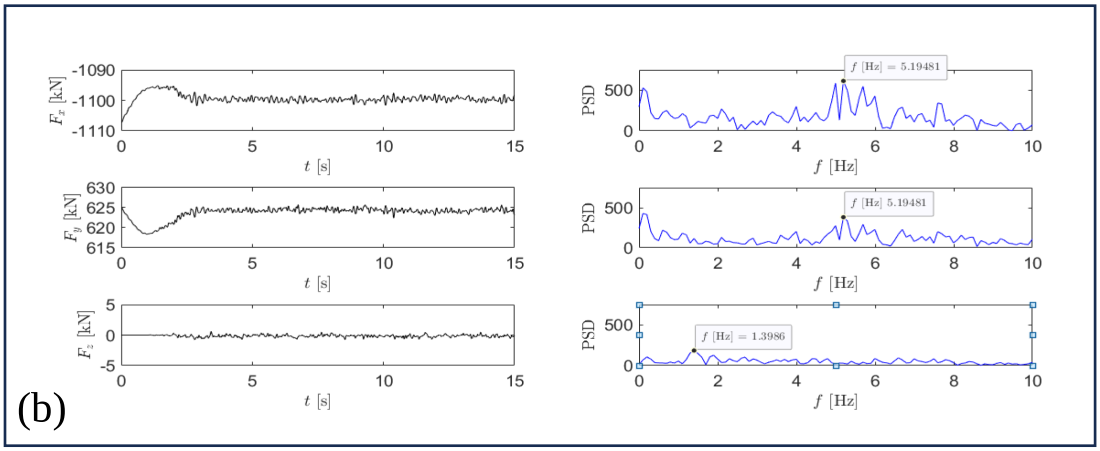


Figure 4. (a) The mass flow rate at boundary when all valves open within 2 seconds, and (b) Time development and spectral characteristics of force components on the piping segment

Figures 4a and 4b show the time development and spectral characteristics of the fluid force on the piping walls in the affected piping segment. The forces in *x* and *y* are not symmetric with the axis of the pipe segment, and thus include a significant pressure component. The z force is symmetric around the axis of the pipe and thus is caused by the shear force and asymmetric fluctuations of the pressure. During the first phase, the valves open in two seconds, causing a gradual change in the force according to the balance of the pressures. As the valves stay open, the fluctuations in the force induced by the turbulent flow are expected to be broadband. In addition, a fluctuating tonal force is observed at 5.2 Hz, which is expected to be related to the branch acoustic excitation by the grazing flow over the cavity mouth.

For the case where CDSV 1 remained closed, results showed that the tonal frequency became concentrated in the x direction and the peak slightly shifted to 5.9 Hz due to the change in the acoustic characteristic of the closed branch.

Steam Reject Piping Modal Analysis Results

The piping modes of vibration in the area of interest, that is, the failed hanger location, are shown in Figure 5. The local horizontal mode vibration frequency is at 16 Hz and the local vertical mode vibration frequency is 27 Hz. As shown in Figure 4b, the dominant frequency of the fluid pressure pulsation forces is roughly 5.9 Hz, so there seems to be no excessive vibrations in the piping response caused by the flow induced pressure pulsations.

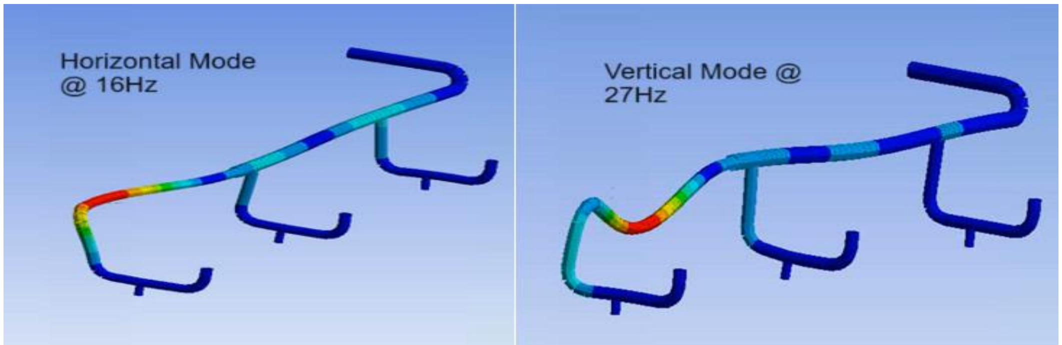


Figure 5. The two dominant local modes of piping vibration

Fluid Structure Coupling Structural Analyses & FFT Transforms

The objective of the fluid structure coupling analysis is to determine steam reject piping response at the location of the failed hanger under the dynamic loads produced by pressure oscillations due to steam flow. The total response will the sum of dead weight load, thermal expansion load and the fluid forces predicted by the fluid dynamic analysis. The vertical displacement (Uy) at the failed hanger location under dead weight and thermal expansion load was 0.001" and 0.008" and the horizonal displacement (Uz) was 0.019" and 0.012" respectively. Fluid loads were established for a total of 17 seconds. First 2 seconds for CSDVs to fully open and then another 15 seconds to get a near steady state piping response. The loads were combined to get total response in vertical and horizontal directions at the failed hanger location.

The displacement response for normal steam reject line operation, i.e., three CSDVs open, was similar to the abnormal operation where one CSDV is stuck closed and only two only two valves are open. The results for the abnormal operation were slightly higher so they are reported in Figure 6. For better visualization of results, only 5 seconds data is plotted in Figure 6. It can be seen that vertical response is much smaller than the horizontal response. The low vertical response is due the fact that piping is well supported vertically in the vicinity of the failed hanger. During the first 2 seconds of CSDVs operation (time for CSDVs to fully open), there is rather strong vibration in the horizontal direction with a maximum range of 0.27" peak to peak. It can be seen that piping response becomes rather constant (range roughly 0.004") near 5 seconds.

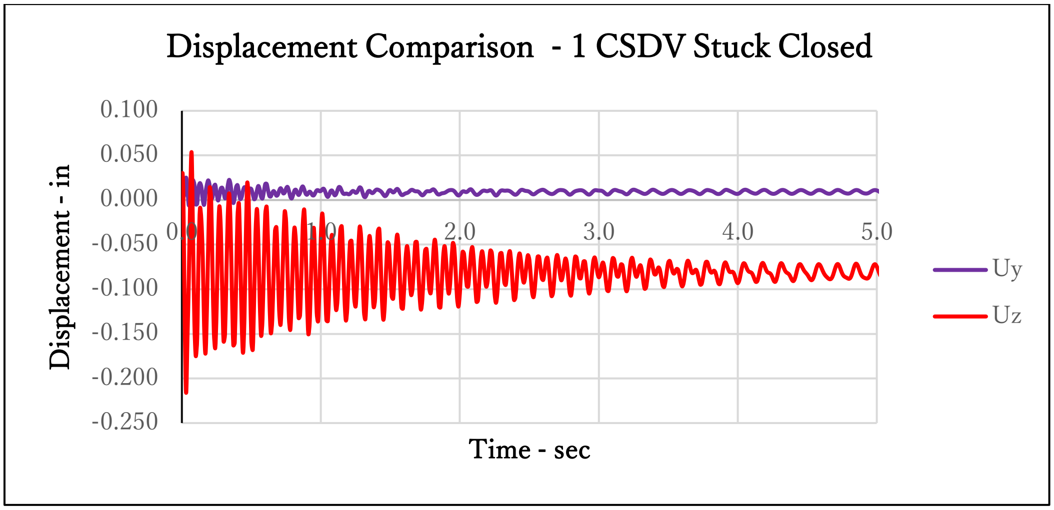


Figure 6. Vertical & Horizontal displacements comparison

The displacement time histories are converted into frequency domain using Microsoft Excel software. The frequency domain results are shown in Figure 7 below. The vertical displacement (Uy) has very, very small peaks at 8 Hz, and 19 Hz. But the horizontal displacement (Uz) has 2 rather large peaks at 8 Hz and 15 Hz. The corresponding amplitudes in horizontal direction are 0.008" and 0.015" respectively. The steam reject system continued operation past the initial 2 seconds operation also induces low amplitude high cycle vibrations in the steady state phase of its operation.

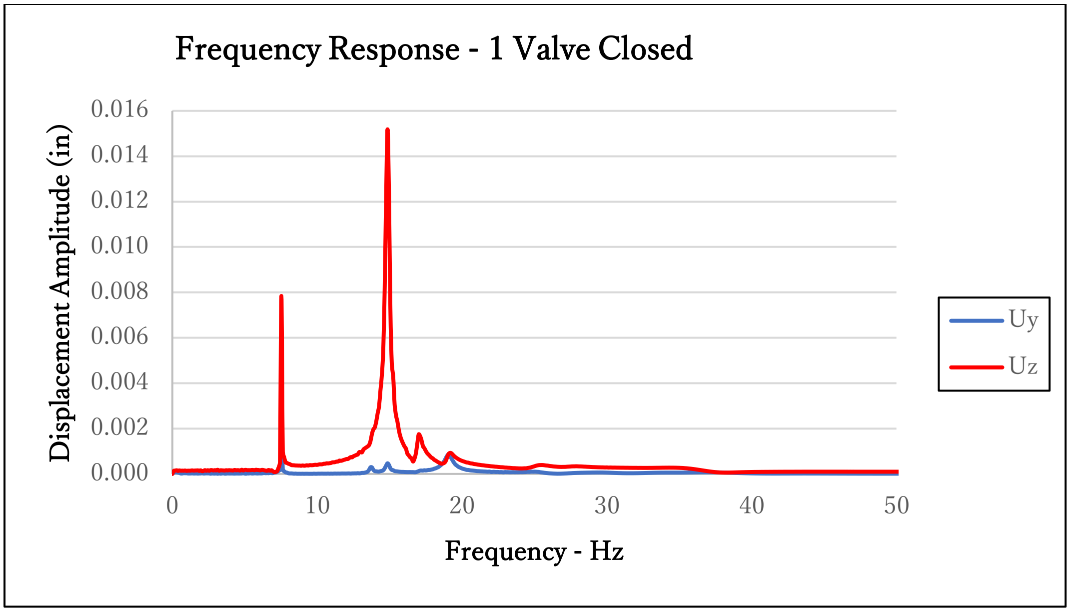


Figure 7. Frequency response, 1 CSDV stuck closed

Failed Hanger Modal Analysis Results

To assess if the hanger failure was influenced by structural resonance between the piping vibration frequency, caused by fluid pressure oscillations, and the failed hanger natural frequencies, a modal analysis of the failed trapeze hanger was carried out. The model consisted of Ansys/Workbench 3D beam elements representing hanger rods and point nodal mass elements to represent spring hanger masses. The hanger rods were supported at the top.

The hanger structure is quite flexible consisting of roughly 120” long ¾” diameter rods. The dynamic behavior is influenced by heavy base beam consisting of two 4”×2” C channels [weight approximately 35 lbf] attached together to form the hanger base and spring hanger point masses (30 lbf each] located near the bottom close to the base of the hanger.

The results show that side to side mode (z direction) with 90% mass participation is at 0.5 Hz and the rest 10% is at nearly 6 Hz. In the vertical direction (y), 20% of the mass participates at 7 Hz and the rest 80% participates at 15 Hz. There are also significant rotational modes in the low frequency range. As shown in Figure 7, there are small peaks in the Uy displacement that match hanger frequencies, but the amplitude is small. The modal analysis results suggest that small portion of the hanger masses are indeed excited by the steam flow pressure oscillations.

CONCLUSIONS

Based on results presented from various analyses, the following conclusions can be drawn:

- During the two seconds taken by CSDVs to fully open, transient vibration takes place in the section of steam reject system near the failed hanger location. The transient vibration is more in magnitude in the horizontal direction than in the vertical direction. The maximum range of peak-to-peak vibration amplitude is nearly 0.27”.

- The vibration amplitudes decrease beyond the first two seconds (full opening of CSDVs) and a steady state is reached afterwards with an amplitude range of 0.004”.
- The Fourier transforms of the steam reject piping displacements, in the vicinity of the failed hanger, yield couple of distinct frequencies of 8 Hz and 15 Hz for the horizontal displacement direction (Uz). The associated amplitudes are 0.008” and 0.015” respectively.
- There appears to be a near match between the horizontal displacement (Uz) frequency of 6 Hz and the hanger modal frequency of 8 Hz suggesting a possibility of small mass excitation in the horizontal direction (Uz).
- In the vertical direction, the piping oscillation frequencies do match hanger natural frequencies, but the amplitude peaks are quite small suggesting little excitation in the vertical direction.
- It is judged from the results that the hanger failure probably results from a combination of small structural excitation and vibration fatigue resulting from low amplitude high cycle piping oscillations during repeated calls to operate the steam reject system.

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