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MECHANICAL VIBRATIONS OF CANDU FEEDER PIPES

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ABSTRACT

This paper presents a numerical dynamic analysis performed to estimate the maximum expected change in the mechanical vibrations of CANDU feeder pipes as a result of a change in flexural support conditions. Finite Element Analysis models are constructed to represent 480 nuclear fuel channels along with their attached inlet and outlet feeder pipes. Each of the 480 models is excited using a random white noise forcing function and the corresponding peak vibration levels are recorded. Two cases are considered to compare the vibration response with the designed support system (On-bearing) and without one support point (Off-bearing). Two types of excitations are considered; flow induced feeder bend and end-fitting excitations. The finite element results obtained from these two independent excitations are used to calculate the ratio between the feeder vibration levels with and without the west inboard end-fitting journal ring support. It is observed that the maximum increase in the expected feeders' vibration peak levels is 20% with the feeder bend excitation while only 2% increase is realized with the application of the end-fitting excitation. It is also observed that the average feeder dynamic peak response to the feeder bends excitation did not significantly change considering the full feeders population. End-fitting excitation results showed a reduction in the calculated average feeders vibration peak responses.

INTRODUCTION

Fuel channels (FC) on typical CANDU reactor are supported on the end-shield plates by journal rings to allow for axial creep elongation. A locking mechanism is used at either the east or the west reactor faces to control the axial position of the fuel channels. Figure 1 illustrates a typical fuel channel and feeders model showing the end-fittings, pressure tube, and attached feeders. Figure 1 also illustrates the support points on the east and west end-fittings. In that particular diagram, the west end is axially locked using a welded stop collar allowing the fuel channel to elongate axially in the east direction. To prevent east side Off-bearing condition, a fuel channel shift in the west direction may be used to reposition the fuel channel axially allowing for additional axial elongation. The west shift program leads to a considerable fuel channel life extension as the axial elongation alternates between the east and west sides. Additional life extension may be obtained by going further allowing the in-board journal ring to lose contact on the west side and rely solely on the stop collar to provide the lateral support. In this paper, it is assumed that the west FC shift will cause a loss of the west journal ring lateral support. This configuration change may change the flexural vibration characteristics of the feeder pipes due to the change in the west end-fitting support conditions. To address the effect of the support condition change on the mechanical vibrations of the feeder pipes, a numerical analysis is performed to assess feeders' mechanical vibrations and compare the on and Off-bearing west scenarios.

Park et. al (2007) presented a three dimensional model of a CANDU fuel channel and studied the free and forced vibration responses under normal and assumed fault conditions. The flow-induced vibrations as the cause of pressure tube excitation are represented by a random transverse force with a unit amplitude. The results are compared with measured data which have been obtained from the reactor noise analyses by using stationary In Core Flux Detector (ICFD) noise signals. It is concluded that the vibration response spectra of a CANDU fuel channel can provide a useful means for detecting and diagnosing the abnormalities during plant operation. Dharmaraju and Rao (2008) presented a dynamic analysis of coolant channel and its internals of Indian 540 MWe PHWR Reactor under simulated loading/fault condition. Similar to Park (2007), the objective is to develop a diagnostics to monitor the health of the coolant channel over its operating life. The IAEA Nuclear Energy Series (2008) also highlighted the use of the ICFD noise signals in detecting and diagnosing the abnormalities in the integrity of fuel channels. As the focus was the fuel channels only, feeders were not included in any of the aforementioned studies.

Olson, David E. (2009) presented the “Pipe Vibration Testing and Analysis” chapter 37 in the Companion Guide to the ASME Boiler & Pressure Vessel Code. This chapter deals with both steady state and transient vibrations. The steady state vibrations are caused by flow turbulence and/or pressure pulsations (among other causes). These steady state vibrations may lead to fatigue failure and are the subject of this paper. The ASME OM-S/G (2003) Operation and Maintenance of Nuclear Power Plants addresses the vibration requirements included in the piping Codes and USNRC Regulatory Guides. The OM Part 3 standard addresses testing requirements and acceptance criteria for piping vibration. The criterion used for steady-state vibration is to limit the vibration stresses to a value below the endurance limit of the piping material. The stress allowable in the OM guide is based on fatigue curves given in Section III of the ASME Code.

CANDU feeders’ mechanical vibrations are customarily assessed using a velocity criterion that may be stated as follows:

$$V_{all} \geq V_{max}$$

Where, V_{all} is the allowable feeder vibration velocity and V_{max} is the expected maximum feeder vibration velocity. Both V_{all} and V_{max} are affected by the change in support conditions. The analysis work covered by this paper addresses the effects of the Off-bearing operation on the maximum expected feeder vibration velocity, V_{max}, (right hand side of the velocity criterion stated above). The velocity criterion for the Off-bearing operation may be stated as follows:

$$V_{all,OFF} \geq V_{all,ON} *VR_{max}$$

Where VR_{max} ($=V_{max,OFF} / V_{max,ON}$) is a conservative measure of the increase in the maximum feeders’ vibration velocity considering the Off/On-bearing configurations. It is noted that the effect of the Off-bearing operation on the allowable feeder vibration velocities (left hand side of the velocity criterion) will be handled in a separate paper.

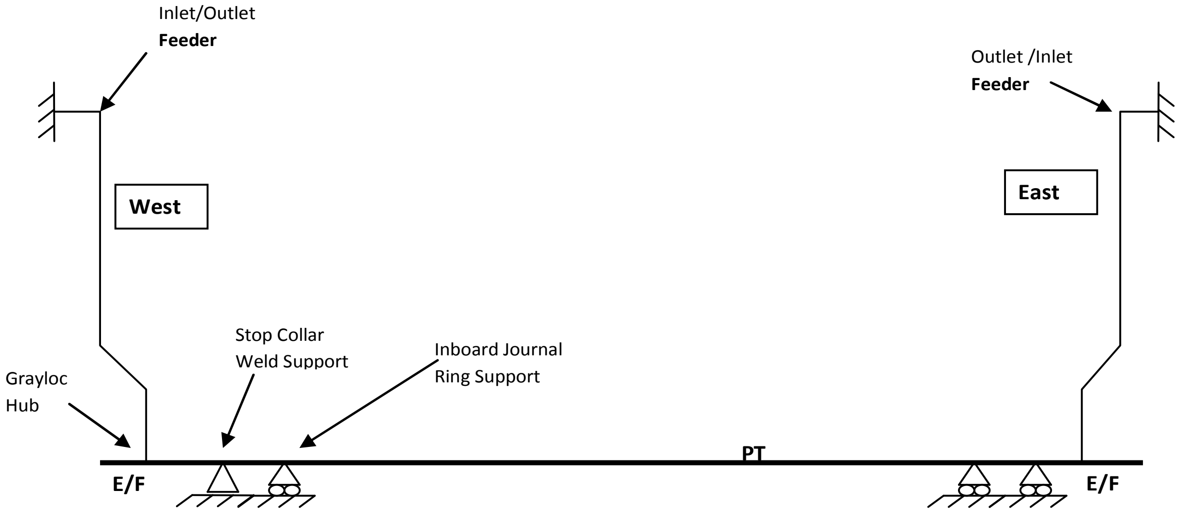

Figure 1: Schematic Fuel Channel/Feeder Model

ANALYSIS METHODOLOGY

Finite element piping analysis models are constructed to represent all 480 fuel channels in a typical CANDU power reactor. Each model is a representation of the fuel channel and the connected inlet and outlet feeders. Since the actual forcing function causing the feeder vibrations is currently unknown, a white noise random function is used to excite the FC and Feeder models. Two independent forcing functions are considered in this analysis; end-fittings excitation and feeder bends excitation. The results presented in this paper are based on the following:

- A uniform maximum west shift displacement (relative to the design condition) is applied on all 480 fuel channels.
- All fuel channels are assumed to operate Off-bearing on the west inboard journal ring support.
- The flow induced excitation remains the same for both On-bearing and Off-bearing operation since the flow path is not significantly changed.
- The analysis of the outlet feeders is performed using the projected end of life thicknesses while nominal thickness values are used for the inlet feeders.
- Only the flexural modes of vibration are considered in this investigation.
- The fuel channel/feeder models are excited using a white noise random function and finite element analysis is performed to obtain the feeders' power spectral density (PSD) response to this forcing function for the on- and Off-bearing configurations.

FINITE ELEMENT MODELING & ANALYSIS

Each fuel channel and its attached inlet and outlet feeders is modeled using the ANSYS PIPE16 linear elastic element with the appropriate flexibility factors and stress indices applied at bends/elbows. The wall thinning due to Flow Accelerated Corrosion (FAC) is uniformly modeled at the tight radius elbow regions for each west and east side feeders. Figure 2 shows a typical FC/Feeder model in the original design configuration. Figure 2 also shows the feeders anchor points at the headers along with the supporting rigid and spring hangers. Figure 3a shows a close up view of the west end-fitting and a portion of the attached feeder in the design configuration (On-bearing) depicting the two support points at the stop collar and the inboard journal ring locations. Figure 3b shows a close up view of the east end-fitting and a portion of the attached feeder showing the inboard and outboard journal ring supports along with equivalent springs to account for bellows. Figure 4 shows a close up view of the west end-fitting without the inboard journal ring support.

Piping Properties

The different groups of piping components on each fuel channel/feeder model are distinguished by applying specific set of real constants to the corresponding elements. Each real constant set defines the pipe outer diameter, thickness, stress intensification factors, flexibility factors, along with the heavy water density.

Material Model

A linear-elastic isotropic material model with the material properties listed in Table 1 is used throughout the analysis.

Table 1: Linear Elastic Material Properties

	Elastic Modulus, psi	Poisson's Ratio	Density, lbf/in^3
Feeders	29.1E6	0.3	0.2835
Pressure Tube	13.5E6	0.4	0.2366
End Fitting	29.1E6	0.3	0.2861
Heavy Water	--	--	0.0395

Feeders' Boundary Conditions

1. All feeders are fixed in all six degrees of freedom at the header anchor points.

2. Rigid hangers and lower cantilever supports (if any) are represented by a vertical spring with 10^6 lb/in spring constant.
3. Spring hangers are modeled with ANSYS' COMPIN14 element using the spring constants as per the design specifications.

Fuel Channel Boundary Conditions

The fuel channel is represented by three major components; east/west end-fittings and the pressure tube in-between.

1. The west end-fitting is supported by equivalent stop collar stiffness values in all six degrees of freedom.
2. The west end-fitting is constrained in the vertical and horizontal directions at the west in-board journal ring location in the case of On-bearing analysis. This support is removed in the case of Off-bearing (West) analysis. The axial (Fuel Channel) direction is left free of constraints.
3. The east end-fitting is supported at the in-board and out-board journal bearings locations in the vertical and horizontal directions. The fuel channel direction is left free of constraints.
4. The east end-fitting is restrained in the rotational direction to reflect the effect of the bellows.
5. The Garter springs separating the pressure and Calandria tubes are represented by horizontal and vertical springs with spring stiffness calculated from a closed form solution of a fixed-fixed beam representation of the Calandria tube.

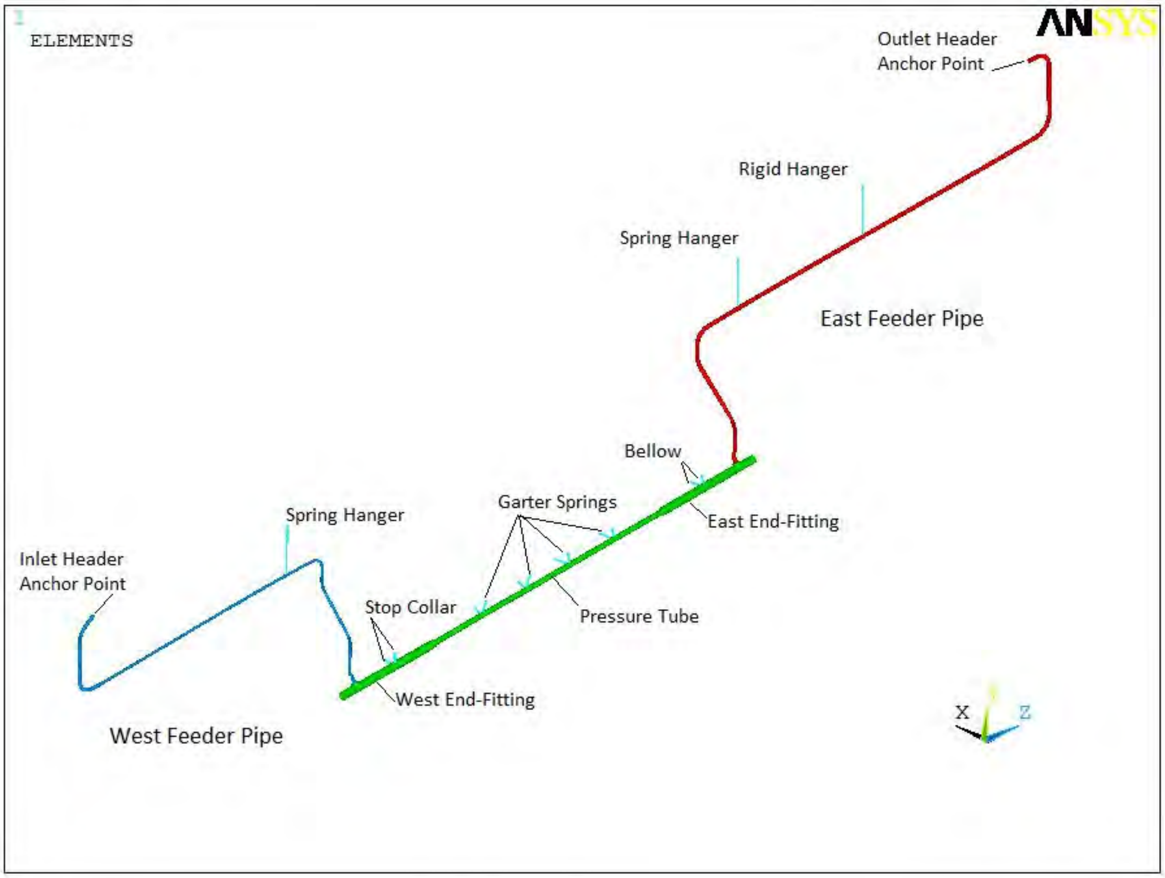

Figure 2: Typical FC/Feeder Finite Element Piping Model

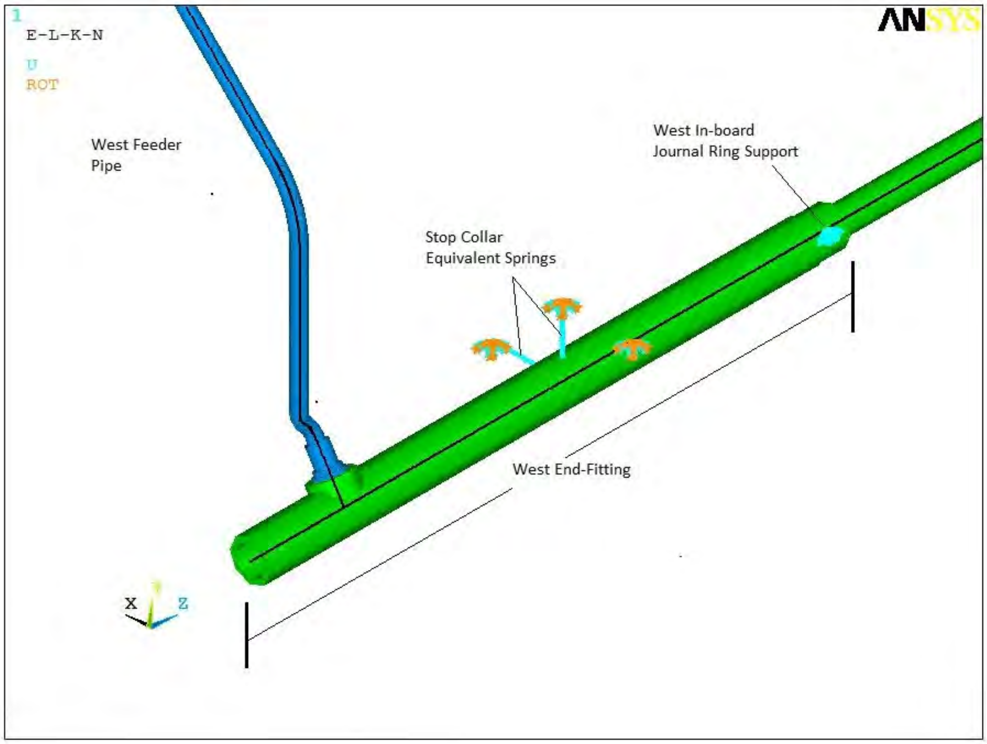

Figure 3a: Close up View of the West End-Fitting & Attached Feeder (On-Bearing Configuration)

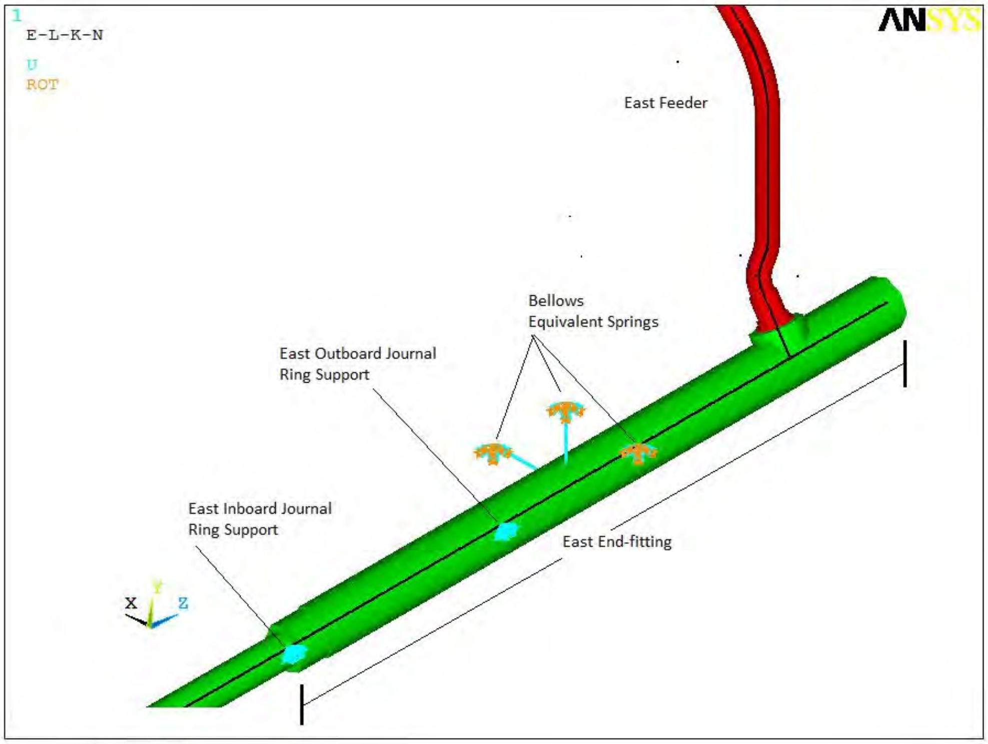

Figure 3b: Close up View of the East End-Fitting & Attached Feeder (On-Bearing Configuration)

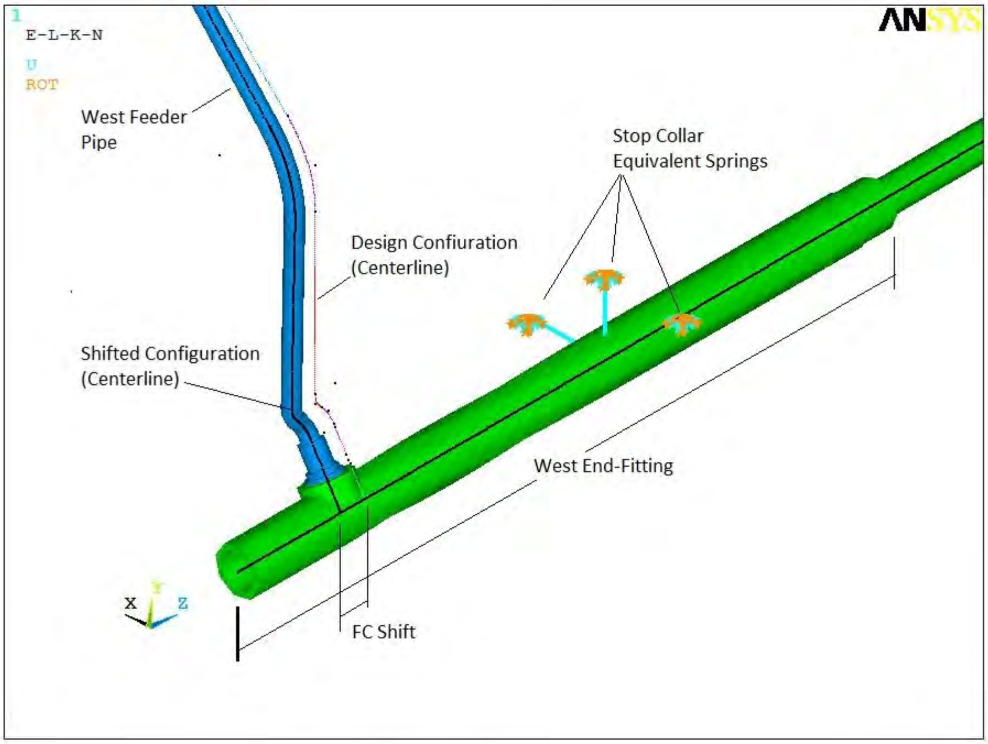

Figure 4: Close up View of Design & Shifted West End-Fitting & Attached Feeder (Off-bearing Configuration)

Analysis Procedure

Each of the 480 FC/Feeder models is analyzed for natural frequencies and mode shapes along with the corresponding stresses within the frequency range of 0-180 Hz. The modal analysis results are post processed to calculate the allowable feeder vibration velocities for the west inlet and outlet feeders. The results of the modal analysis are also used to perform the power spectral density analysis using the modal superposition technique. The results of the PSD analysis are post processed to calculate the feeders vibration peak velocities.

The analysis procedure is organized as follows:

1. Perform modal analysis within the frequency range of interest (0-180Hz) to determine the natural frequencies, mode shapes, and corresponding stresses.
2. Perform PSD FEA of the On-bearing models to obtain the vibration velocity response to the end fittings random excitation. Determine the maximum feeder-specific vibration velocity for the On-bearing configuration, $V_{max,ON}$.
3. Perform PSD FEA of the Off-bearing (West) models to obtain the vibration velocity response to the end fitting random excitation. Determine the maximum feeder-specific vibration velocity for the Off-bearing (West) configuration, $V_{max,OFFt}$.
4. Determine the vibration velocity ratio for each individual feeder as follows:
$$VR_i = V_{max,OFF} / V_{max,ON}$$
5. Determine the global maximum vibration velocity ratio from the end-fitting excitation VR_1,
$$VR_1 = \mathrm{Max}\ (VR_i)$$
6. Repeat for feeder bend excitations with the application of the bend forces instead to calculate VR_2.
7. Determine the global maximum feeder vibration velocity ratio,
$$VR_{max,OFF} = \mathrm{Max}\ (VR_1, VR_2)$$

FEA Power Spectral Density Dynamic Analysis

Two types of random excitations are considered; End-fitting and Feeder Bend. The magnitude of these forces is irrelevant to the analysis results considering that the analysis is linear and the target outcome is the ratio between the vibration response on and Off-bearing configurations.

End-Fitting Excitation:

The uniform feeder end-fitting excitation is considered as a representation of the flow induced random vibrations as a result of the turbulence nature of the fluid flow in the fuel channel. A unit end-fitting excitation is applied simultaneously in two planes on both the west and east end-fittings in the horizontal (Z-X) and vertical (Y-Z) directions, respectively.

Feeder Bend Excitation:

The feeder bend excitation is introduced as a representation of the flow induced vibrations as the heavy water flows through the curved sections of the feeder pipes. The bend forces are applied at the beginning and end of each individual bend in the tangent directions. In addition, forces are applied at the beginning and end of reducers to account for the change in cross section area.

FINITE ELEMENT ANALYSIS RESULTS

The results obtained from the modal and PSD analyses in ANSYS of all 480 west feeders are post processed in Microsoft Excel spreadsheets. The result of interest in this article is the peak vibration velocities on and Off-bearing. Figure 5 shows a comparison between the peak feeders' vibration velocities Off-bearing against the On-bearing configuration. The vibration velocities are normalized using the maximum feeders' peak velocity On-bearing. It is evident from Figure 5 that the end-fitting excitation produces a decrease in the peak feeder vibration velocities when the in-board journal ring support on the west side is not active. On the other hand, the feeder bend excitation shows both increase and decrease in the peak feeder vibration velocities going from the On-bearing to the Off-bearing configuration. Same observations are valid whether the full feeder population (Figure 5), outlets only (Figure 6), or inlets only (Figure 7) are considered in the comparison.

These observations are more evident when checking the histograms of the feeders peak vibration velocities as shown in Figure 8, Figure 9, and Figure 10 for the full population (outlets + inlets), the outlets only, and the inlets only, respectively. Figure 8 (a) shows the histogram of the feeders peak vibration velocities for the on and Off-bearing configurations under the end-fitting excitation. As can be observed, the mean value of the peak vibration velocities is lower for the Off-bearing configuration. Figure 8 (b) shows the histogram of the feeders peak vibration velocities for the on and Off-bearing configurations under the feeder bend excitation. This figure indicates that the mean value of the peak feeder vibration velocities is essentially unchanged whether it is from on or Off-bearing configurations. Figure (c) shows the histograms of the velocity ratio ($V_{max,OFF}/V_{max,ON}$) for all outlet and inlet feeders on and Off-bearing. As can be seen, the mean value is close to unity for the bend excitation case and the maximum is 1.20. Figure 9 and Figure 10 depict the histograms for the outlets and inlets only, respectively.

Table 2 summarizes the statistics of the peak feeder vibration velocities for the whole population, outlets only, and inlets only. The table shows that the maximum increase in the feeders peak vibration velocity of 20% is obtained from the inlet feeders population. The maximum increase in the peak vibration velocity for outlets only is 13%.

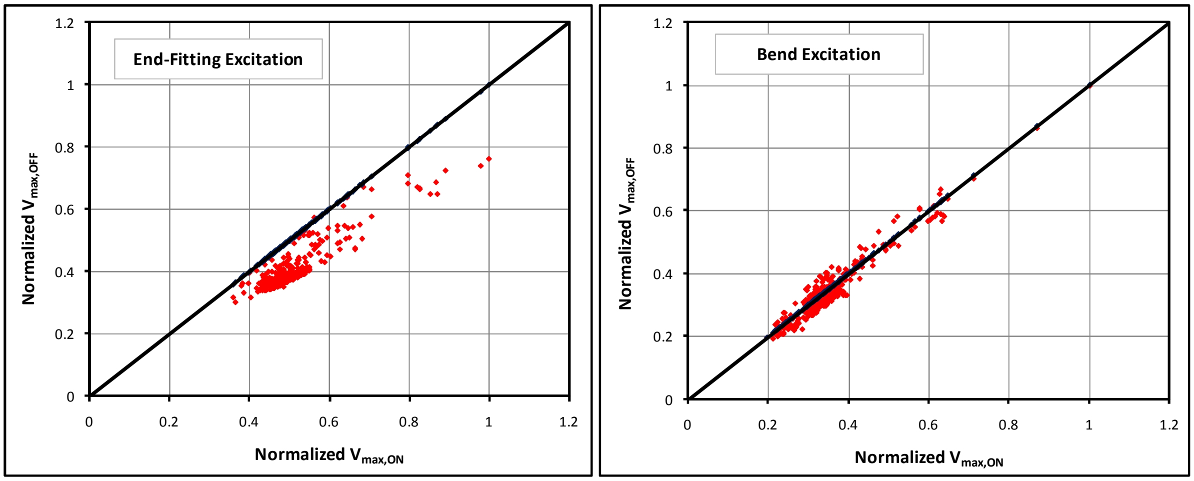

Figure 5: Maximum Inlet & Outlet Feeders Vibration Velocity – OFF vs. On-bearing

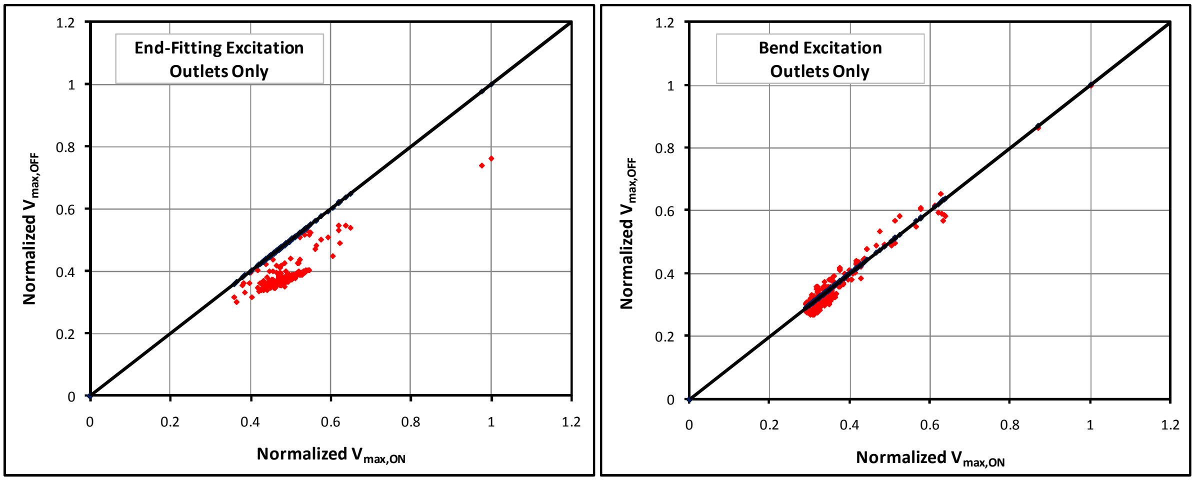

Figure 6: Maximum <u>Outlet</u> Feeders Vibration Velocity – OFF vs. On-bearing

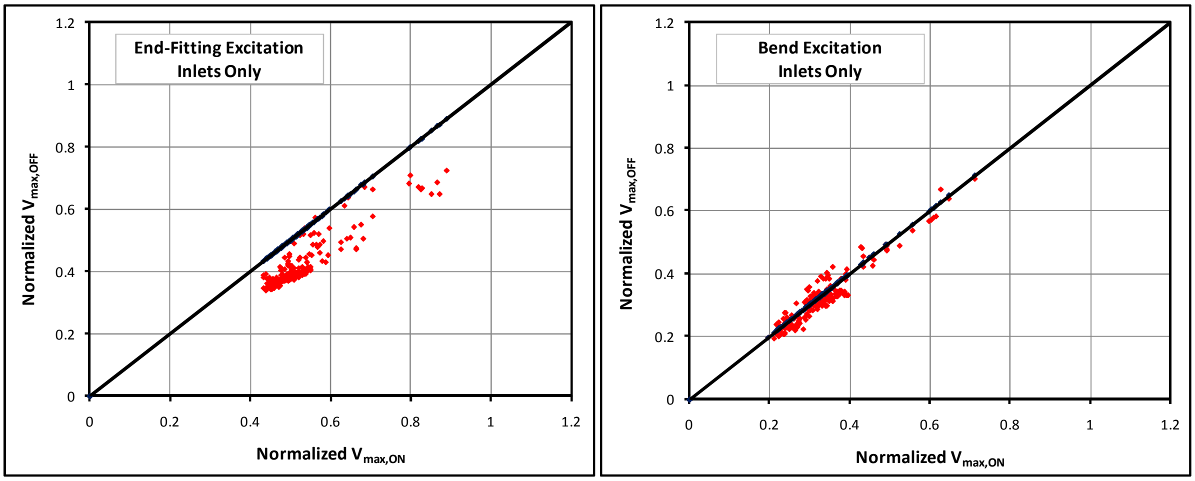

Figure 7: Maximum <u>Inlet</u> Feeders Vibration Velocity – OFF vs. On-bearing

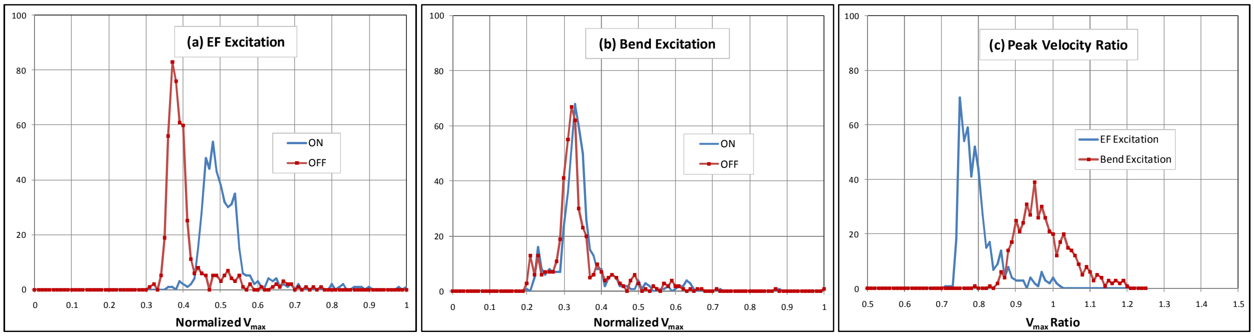

Figure 8: Normalized Maximum Inlet & Outlet Feeders Vibration Velocity Histogram

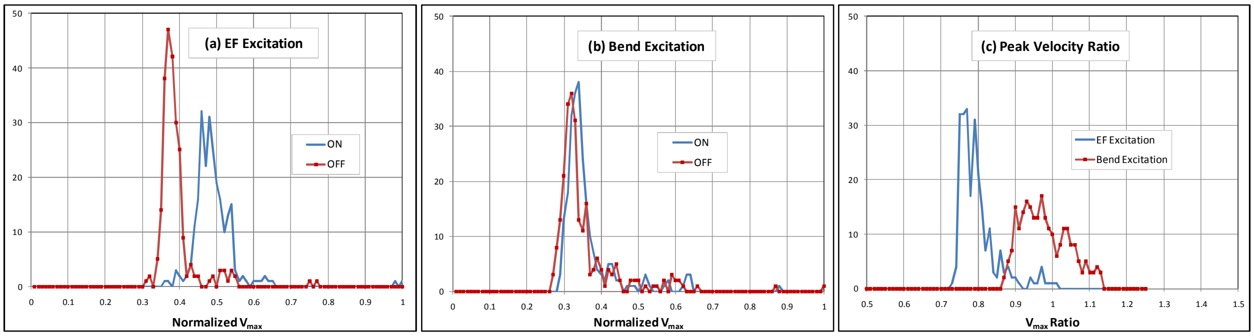

Figure 9: Normalized Maximum Outlet Feeders Vibration Velocity Histogram

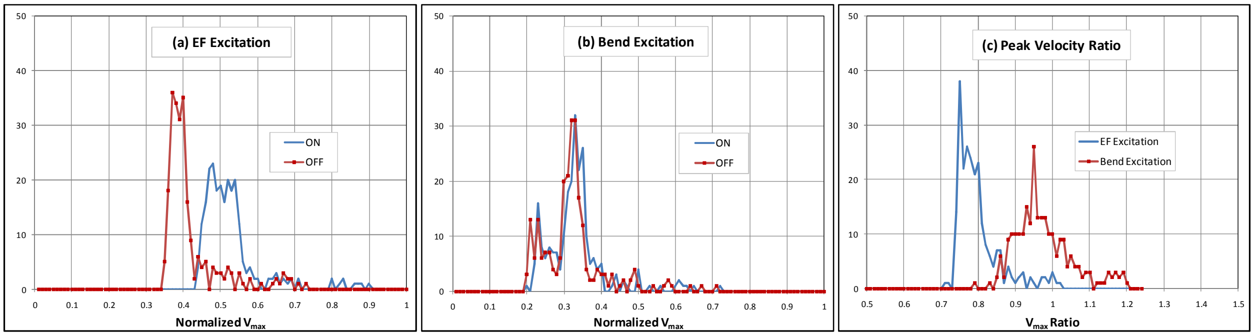

Figure 10: Normalized Maximum Inlet Feeders Vibration Velocity Histogram

Table 2: Statistics of the Feeders Peak Velocity Ratio (off/on)

	End Fitting Excitation			Bend Excitation		
	All	Outlets	Inlets	All	Outlets	Inlets
Minimum	0.71	0.72	0.71	0.79	0.86	0.79
Maximum	1.02	1.00	1.02	**1.20**	**1.13**	**1.20**
Average	0.79	0.79	0.79	0.97	0.97	0.97

SUMMARY & CONCLUSIONS

Analysis models are constructed to represent 480 CANDU reactor fuel channels along with their attached inlet and outlet feeders. All 480 fuel channel/feeder models are dynamically excited with uniform random function covering a frequency range of 0-180Hz and the corresponding maximum feeder vibration velocities are calculated for the on and Off-bearing conditions. Two types of excitations are considered; end-fitting excitation and feeder bends excitation. The analysis results indicated the following:

- With the end-fitting excitation, it is observed that the maximum expected feeder vibration velocities for the Off-bearing condition are lower than that of the On-bearing condition.
- The feeder bends excitation, on the other hand, produces higher vibration response for the Off-bearing condition. The maximum recorded increase is 20% observed for a very limited number of feeders. As a whole population, the average peak feeder vibration velocity is slightly lower for the Off-bearing condition compared to the On-bearing condition.
- The maximum expected feeder vibration velocities distributions for the on and Off-bearing operation are essentially the same for the whole population and for the outlets or inlets only.

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