Full Paper Transactions, SMiRT 28
Toronto, Canada, August 10-15, 2025

Experimental Investigation of Vibration-Induced Neutron Noise in the ZED-2 Research Reactor. Part I: Vibration Assessment to Support Safety Analysis

Ibrahim Gad-el-Hak*, Paul Feenstra, Mohammed Alziadeh, Brendan St. Pierre, Michael Burlock, Salim El Bouzidi

Canadian Nuclear Laboratories, Chalk River, ON, Canada
***Corresponding Author. E-mail Address: Ibrahim.gadelhak@cnl.ca**

ABSTRACT

Mechanical vibrations of reactor core internals can lead to fluctuations in the neutron flux field, which are also known as reactor neutron noise. Analyzing neutron noise for abnormalities can potentially provide an early warning for issues and allow the diagnosis of malfunctions, which can be extremely useful for operating nuclear reactors. The neutron noise induced by mechanical vibrations has been numerically examined in the literature. However, experimental research on this practical issue is still quite limited.

The main aim of this study is to investigate experimentally the effect of vibration of a neutron absorber on the reactor neutron noise. This is part of a research program currently underway at the Zero Energy Deuterium (ZED-2) nuclear research reactor at Canadian Nuclear Laboratories (CNL), Chalk River site. Introducing a controlled mechanical vibration absorber on a fuel channel inside the ZED-2 reactor is a challenge in terms of reactor operation, as it may unintentionally cause mechanical vibrations in other fuel channels within the reactor. Therefore, conducting a vibration assessment to support the safety analysis for the ZED-2 experiment for vibration-induced neutron noise is imperative.

Part I of this two-part paper presents the safety analysis for vibrating an absorber attached to a fuel channel. A reduced scale mock-up of the ZED-2 reactor was designed and built at the Chalk River Laboratories to measure cross-coupling responses between tubes due to a vibrating tube. The mock-up tube array was designed to mimic the fuel channels in ZED-2. A group of five tubes surrounding the vibrating tube are instrumented with strain gauges to measure their responses at different excitation frequencies. The ZED-2 mock-up experiments showed that the surrounding tubes are only strongly coupled with the vibrating tube when the forced motion of the vibrating tube coincides with the lowest resonant frequency of the instrumented tubes. The equation of motion of a fuel channel has been derived to calculate its dynamic response. The hydrodynamic forces are then included in this equation to compute the dynamic responses of the ZED-2 fuel channels. Numerical analysis supported the selection of test parameters for the ZED-2 experiment.

INTRODUCTION

Neutron flux fluctuations resulting from flow-induced vibration (FIV), temperature changes, and density variations in a reactor core are referred to as neutron noise [1]. Although these variations are typically undesired, they include information that can be carefully extracted for reactor on-line monitoring and diagnostics. The main benefit of online monitoring is that it is non-intrusive, meaning no additional sensors need to be used in high radiation environments. The analysis of neutron flux fluctuations, measured by both in-core and ex-core detectors, can be used to detect anomalies in the primary side of power reactors. Of particular interest here is neutron noise caused by mechanical vibrations of reactor core components due to coolant flow. Mechanical vibrations can lead to fuel failures and the release of radioactive products from fuel rods. Fry et al. [2] analysed abnormal flux oscillations from ex-core detectors in the Palisades nuclear plant. The neutron noise was attributed to abnormal movement of the core barrel, and this was confirmed during an on-site inspection. Antonopoulos-Domis [3] theoretically studied the effect of fuel rod vibrations on reactivity and neutron density noise. It was found that when a fuel rod vibrates at its fundamental

frequency, f_1, both reactivity and neutron density exhibit peaks at its fundamental frequency, f_1, and its harmonics. The neutron flux depression near the vibrating rod was responsible for generating harmonics into the reactivity fluctuations. More recently, Vidal-Ferràndiz et al. [4] performed numerical simulations in both the time and frequency domains to study the influence of mechanical vibrations of fuel assemblies on the neutron flux in a reactor core. They found that the neutron flux oscillated at the same frequency as the mechanical vibrations of the fuel assembly. This conclusion aligns with the findings of Antonopoulos-Domis's model. Moreover, Pázsit and Glöckler [5, 6] developed a theoretical model to localize a failed fuel rod using in-core neutron flux detectors. They found that a minimum of three detectors was required to triangulate the location of the failed fuel. A major shortcoming of previous research work is the lack of validation with experimental results. The transfer function between mechanical vibration and neutron noise needs to be determined to gain a deeper understanding of the dynamics of neutron noise caused by mechanical vibrations. This would enable more effective reactor noise diagnostics for quantifying mechanical vibrations of the reactor core internals.

This work is conducted to experimentally investigating the effect of mechanical vibrations on neutron flux in the Zero Energy Deuterium (ZED-2) nuclear research reactor at Chalk River Laboratories. The ZED-2 experiment consists of attaching a miniature shaker, designed in-house, to a fuel channel to vibrate a flat plate. The flat plate acts as a neutron absorber. The neutron fluctuations are then measured by in-core flux detectors positioned around the reactor core, and an ex-core flux detector. The dynamical parameters of the mechanical vibrations, vibration amplitude and frequency, are controlled by the shaker to understand the effect of these parameters on the neutron field. The challenge with conducting this experiment lies in the fact that the inertia force generated by the vibrating plate may trigger vibrations in the fuel channel where the shaker is attached. Consequently, neighbouring fuel channels may also experience vibrations due to hydrodynamic coupling within the fuel channel array. Before conducting neutron noise experiments in ZED-2, it is essential to verify that the induced vibration in the reactor does not compromise safety protocols for operating the reactor. Considering this problem, it is imperative for practical and safety reasons, to characterize the dynamics of a tube array that mimics the ZED-2 fuel array when exposed to vibrations induced by a single fuel channel.

The vibratory behaviour of structural components of nuclear reactors, such as reactor internals, steam generator tube bundles, and nuclear fuel bundles, requires consideration of the dynamic interaction between the fluid and the structure. Hydrodynamic forces associated with fluid motion are responsible for determining the structural response [7]. Yu and Vanburen [8] developed a finite element structural code in determining the hydrodynamic mass (i.e. fluid-added mass) of a fluid-structure system; however, the fluid motion was modeled as ideal fluid flow (i.e. inviscid and incompressible). The dynamic analysis was performed for a 2x2 square tube array with a pitch-to diameter ratio of 1.33, submerged in a square container filled with water, to determine its natural frequencies in both air and water. The numerical results indicated that the frequencies of the tube array in water were significantly lower than those in air. The added mass coefficient ($C_m = m_{Added}/m_{Tube}$) was 1.05, where m_{Added} (Kg/m) represents the inertia imposed by the surrounding fluid and m_{Tube} is the mass of the tube per unit length (Kg/m). Moretti and Lowery [9] conducted experimental measurements of the added mass coefficient for a single flexible tube within square and normal triangle tube arrays with pitch-to-diameter (P/D) ratios ranging from 1.25 to 1.5. The experiments showed that the hydrodynamic mass (m_{Added}) is influenced by the geometry of the tube array, the density of the fluid, and the tube diameter. For square tube arrays, the added mass coefficient ranged from 1.272 to 1.519 for P/D varying from 1.5 to 1.25.

The ZED-2 reactor is a tank-type, heavy-water moderated, low-power research reactor. The ZED-2 fuel channels are arranged in a square lattice array with a P/D ratio of 2.24. The fuel channels are partially submerged in water, with the water level carefully controlled to maintain the reactor's criticality and power output. Research on the fluid-dynamic coupling of a vibrating tube within a tube array with a P/D of 2.24, partially submerged in still water is limited in the literature.

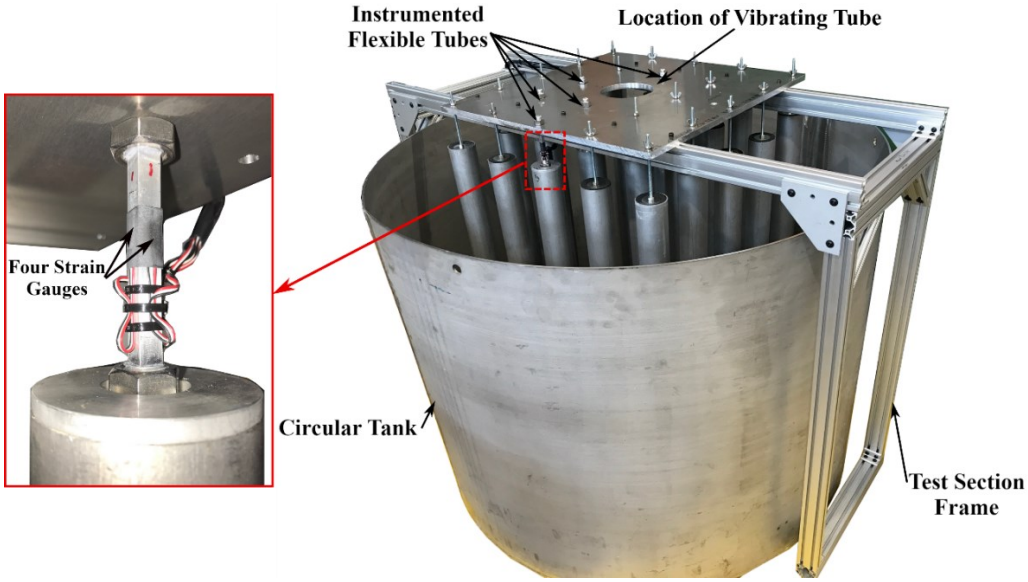
The work reported here in Part I of this two-part paper aims to provide a vibration assessment for conducting the vibration-induced neutron noise experiment inside the ZED-2 reactor. The work consists of experimental measurements and theoretical model development. A mock-up of the ZED-2 tube array is

designed and fabricated to measure its dynamical behaviour under different excitation frequencies. A theoretical model of the ZED-2 fuel channel has been developed to evaluate the modal parameters and dynamic responses of the fuel channel array under various excitation frequencies.

EXPERIMENTAL APPARATUS

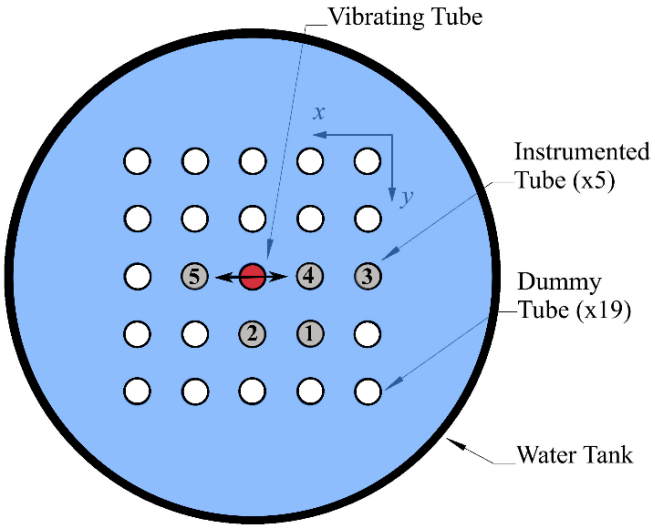
The vibration-induced neutron noise experiment in ZED-2 consists of a flat plate mounted on a miniature electrodynamic shaker. The miniature shaker was developed and fabricated at Canadian Nuclear Laboratories (CNL) to withstand high radiation and wet environments. The plate-shaker assembly is attached to a fuel channel with a split-clamp. The inertia force generated by the vibrating plate can induce vibrations on the fuel channel equipped with the plate-shaker assembly.

The ZED-2 reactor consists of a large aluminium tank surrounded by a graphite reflector and concrete shielding. Fuel assemblies are hung in the calandria from steel beams with the fuel arranged in virtually any desired configuration [10]. A test section has been designed to mimic the geometry of the ZED-2 fuel array. The test section includes three main components: a tube array, a circular stainless-steel tank, and a vibrating tube. The tubes are arranged in a square lattice (5x5) with a *P/D* of 2.24, identical to the *P/D* of the fuel channel arrangement in ZED-2. This tube array replicates a section of the ZED-2 reactor. A flexible tube design, consisting of a hollow tube suspended from a square beam, enables flexibility in both the x- and y-directions. Solid cylinders are placed inside the mock-up tubes to replicate the weight of the fuel in the fuel bundles. The tubes are suspended from one end, from a plate, and submerged in an open tank as shown in Figure 1(a). The figure shows the mock-up apparatus without the central vibrating tube. The tube array consists of 19 dummy tubes and 5 flexible tubes. Each flexible tube exhibits a natural frequency (f_n) of 1.59±0.030 Hz in air. The natural frequency of the flexible tubes was determined via a free decay test (described in subsequent sections). The vibrating tube is installed at the centre of the array as shown in Figure 1(b). A group of five tubes surrounding the vibrating tube (see Figure 1(b)) are instrumented with strain gauges to measure their responses. Each tube is instrumented with four strain gauges near the clamping location of the flexible beam as shown in Figure 1(a).



(a)

Figure 1. *Cont.*



(b)

Figure 1. (a) Test section setup and (b) locations of the instrumented tubes and the vibrating tube in the array.

To induce vibrations in the array, the central (vibrating) tube is linked to a shaker as shown in Figure 2. This tube is pivot mounted on an aluminium extruded frame, which is separate and isolated from the test section frame, and the rest of the test rig. The shaker-central tube assembly is mechanically isolated from the test rig to ensure that oscillations in the flexible tubes are due to hydrodynamic interactions and not a consequence of mechanical vibrations from the shaker-central tube assembly. The force from the shaker is transmitted to the central tube via a pivot coupling between the stinger rod and the tube, as shown in Figure 2. A force sensor is installed between the pivot coupling and the vibrating tube to measure the input force exerted on the tube. To measure the displacement of the central tube, a laser displacement sensor is pointed at a flat surface attached to the tube, as shown in Figure 2. The tube is excited over a range of frequencies to see the effect of the excitation frequency (f) on the tube array response.

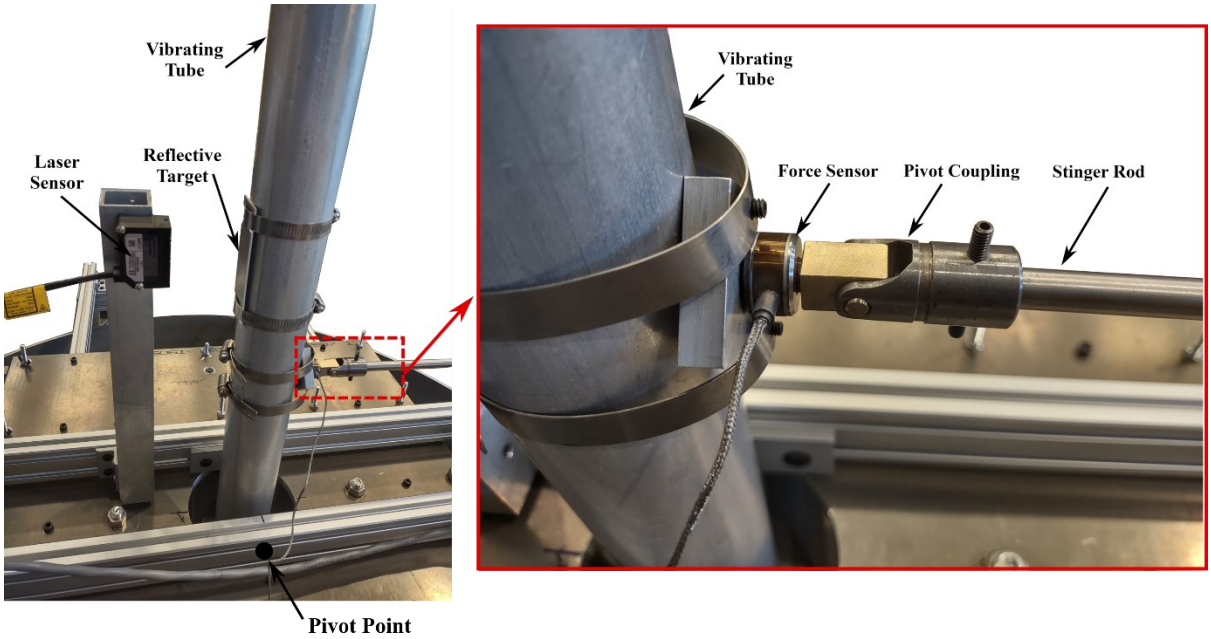


Figure 2. Design and instrumentation of the vibrating tube.

A data acquisition system is used to monitor and record the signals from the laser sensor, force sensor, and strain gauges using LabVIEW software. Figure 3 shows the final test apparatus setup used for investigating the hydrodynamic interactions induced by tube vibrations in the ZED-2 fuel assembly mock-up.

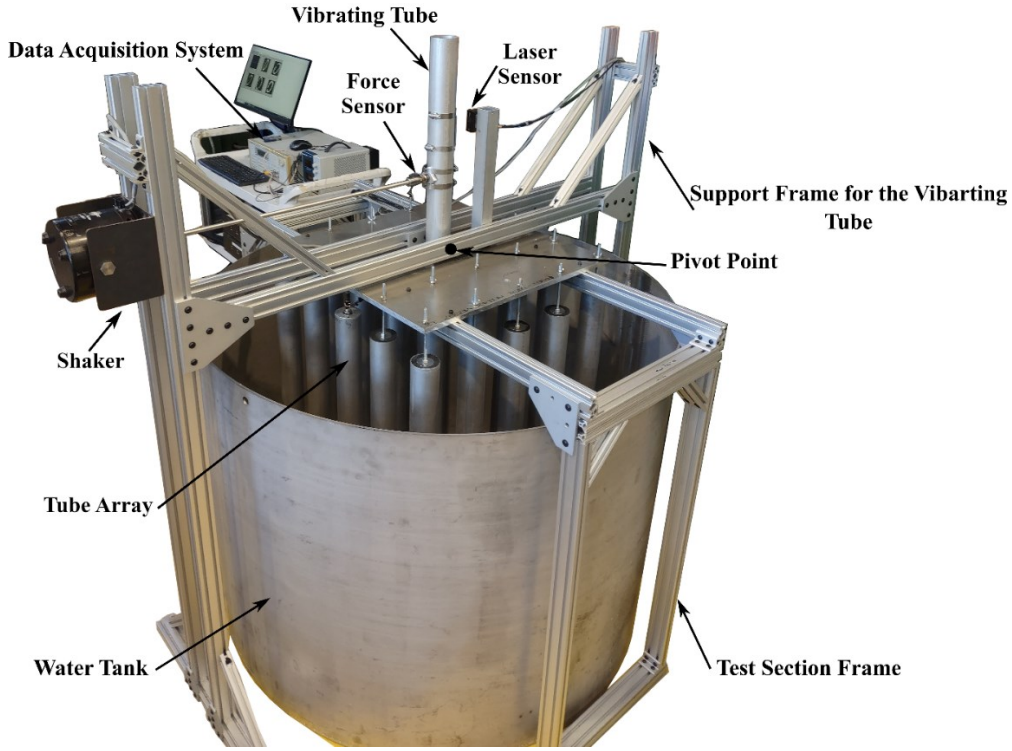


Figure 3. Final test apparatus setup.

In the experiments, the excitation frequency was induced at discrete frequencies ranging from 1.30 Hz to 6.00 Hz in water. This range was selected to cover frequencies spanning either side of the resonance frequency. To measure the tube displacement across this frequency range, the shaker applied a constant force of approximately 5 N (zero-to-peak) while varying frequency from 1.30 Hz to 6.00 Hz in water. Figure 4 shows how the displacement of the vibrating tube, at a point where the laser sensor is focused, varies inversely with the excitation frequency (f). The tube displacement decreases as the frequency increases for a given acceleration.

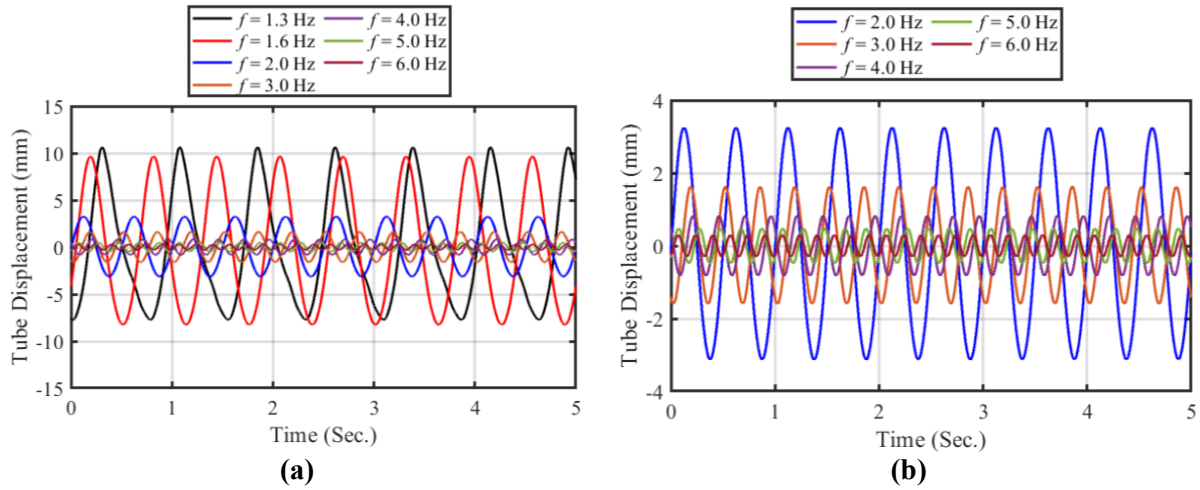


Figure 4. Vibrating tube displacement in water as a function of excitation frequency (f): (a) $f = 1.3$ Hz to 6.0 Hz, and (b) $f = 2.0$ Hz to 6.0 Hz.

EXPERIMENTAL RESULTS

The responses from the five instrumented tubes are measured when the central tube is excited in the x-direction by the shaker. The x-direction is denoted as the direction parallel to the excitation direction, as illustrated in Figure 1(b). Figure 5 shows the tube array vibration in the x- and y- directions at an excitation frequency of 1.30 Hz. In the figure, the tube displacement amplitude is measured at the line of action. The line of action is calculated based on the hydrostatic pressure exerted on the tube. The results show that tubes 2, 4, and 5, which are closest to the central (vibrating) tube, exhibit the highest amplitudes in the array, attributed to the strong hydrodynamic coupling. Figure 6 shows the mode shape of the tube array at $f =$ 1.30 Hz. The tube amplitude is scaled up by a factor of 5 for clarity in the figure. The tubes are most strongly coupled in the excitation direction (x-direction). To examine how the excitation frequency impacts the response of the tube array, the excitation frequency is gradually increased by 0.05 Hz increments up to 1.50 Hz. Figure 7a, 7b, 7c, and 7d show the tube array mode shape obtained at four excitation frequencies, $f =$ 1.35 Hz, 1.40 Hz, 1.45 Hz, 1.50 Hz, respectively. Large amplitude vibrations are observed at frequencies of 1.35 Hz, 1.40 Hz, and 1.45 Hz, indicating that the tube array is resonating.

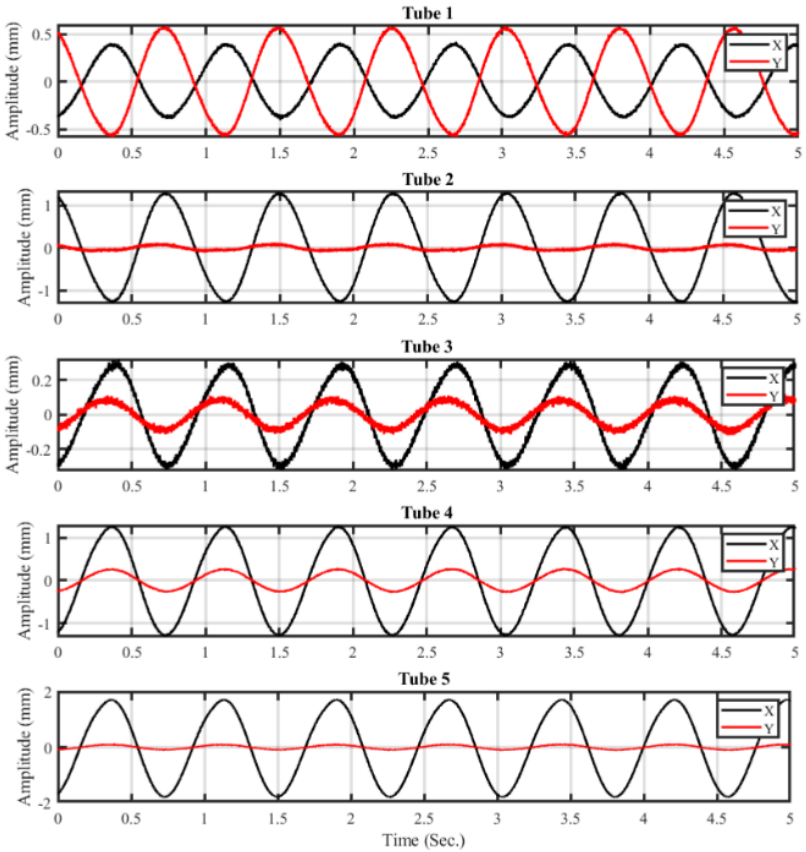


Figure 5. Tube array response at an excitation frequency (f) of 1.30 Hz.

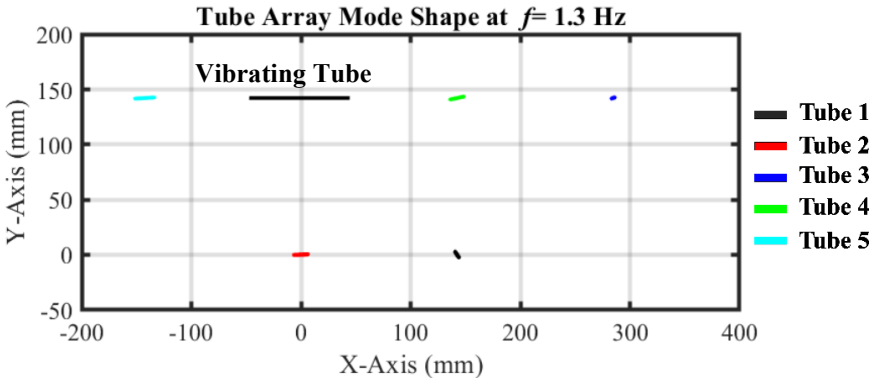


Figure 6. Tube array mode shape at f = 1.30 Hz.

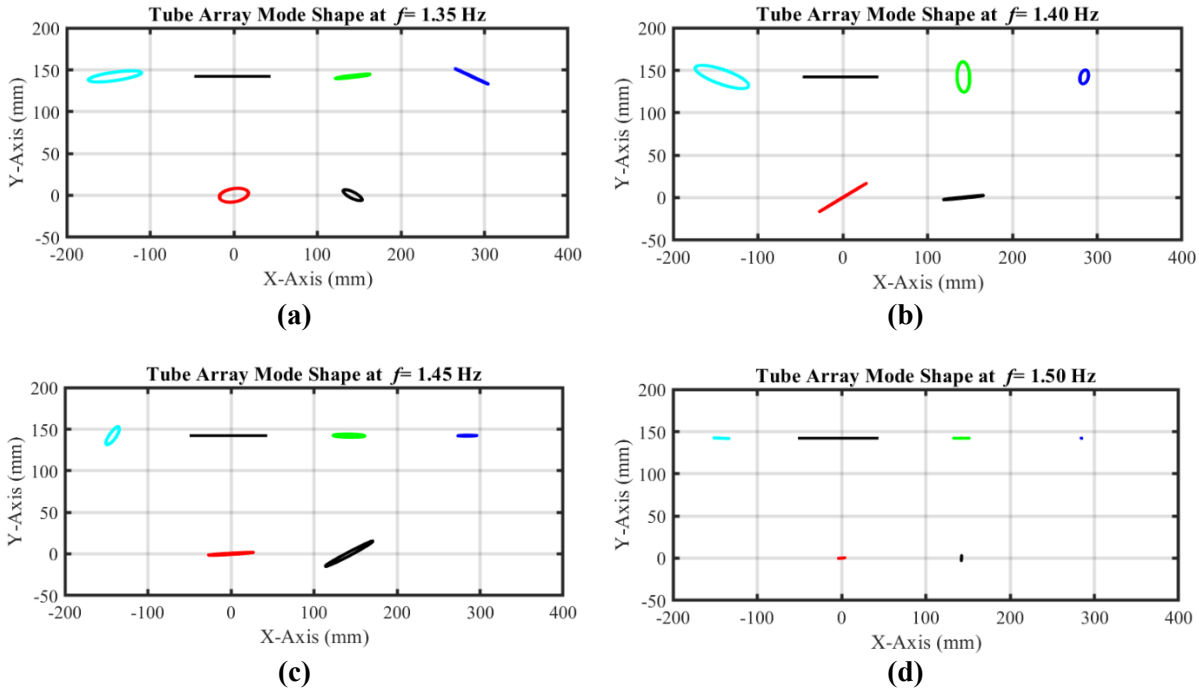


Figure 7. Tube array mode shapes obtained at different excitation frequencies: (a) $f = 1.35$ Hz, (b) $f = 1.40$ Hz, (c) $f = 1.45$ Hz, and (d) $f = 1.50$ Hz.

Figure 8 shows the amplitude ratios between the surrounding tubes and the vibrating tube in the x- and y-directions as functions of the frequency ratio (f/f_n). The maximum amplitude ratio in the x-direction is nominally 0.25 at the resonant frequency of the tube array in water while the ratio reduces to 0.15 in the y-direction. At f/f_n = 1.07, the amplitude ratio decreases sharply to 0.01 in the x-direction and 0.005 in the y-direction. The sharp decrease in the normalized amplitudes at $f/f_n \geq 1.07$ indicates that the tube array is outside the resonance range, and thus, are weakly hydrodynamically coupled.

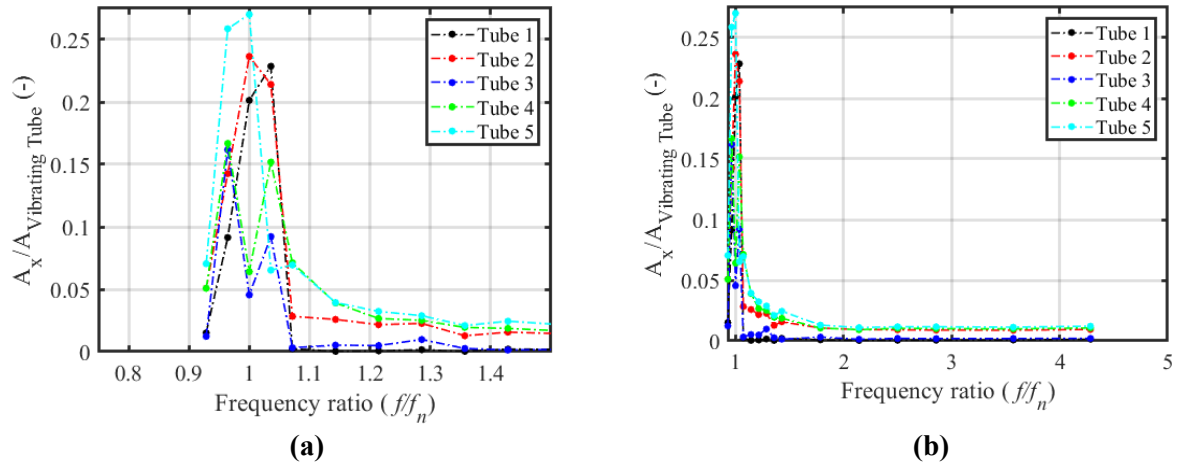


Figure 8. *Cont.*

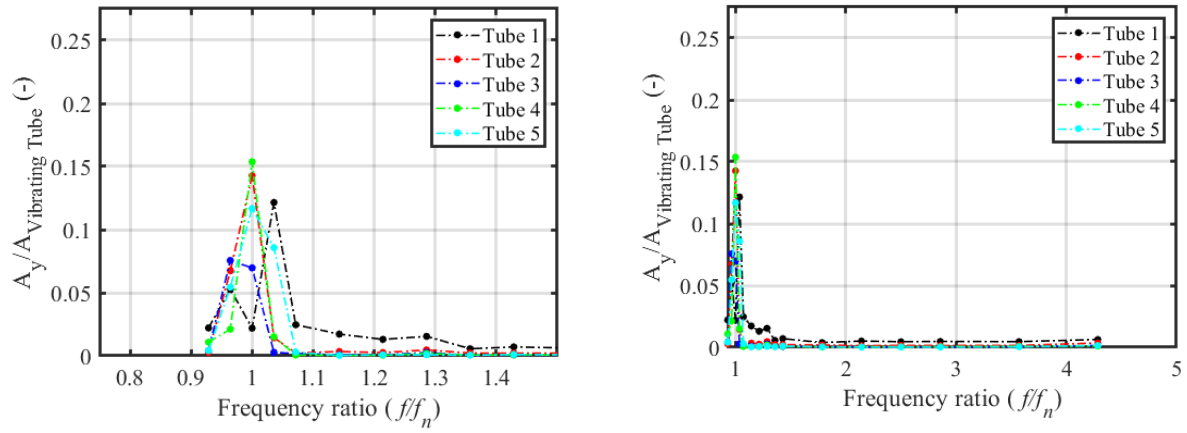


Figure 8. Amplitude ratios between the surrounding tubes and the vibrating tube in the x- and y-directions as functions of the frequency ratio (f/f_n): (a) & (b) for $A_x/A_{Vibrating\ Tube}$, and (c) & (d) for $A_y/A_{Vibrating\ Tube}$.

DYNAMIC BEHAVIOUR OF THE ZED-2 FUEL CHANNEL ARRAY

Cross-Coupling Fluid Forces Estimation

The prediction of the fuel channel array response in the ZED-2 reactor induced by the vibrating plate has been carried out in three steps. The first step is to estimate the fluid forces acting on the mock-up tubes using the measured responses from the mock-up experiments. The force coefficients will then be computed using the test and modal parameters of the mock-up tube array. Finally, the fluid forces acting on the fuel channels will be estimated using these force coefficients derived from the reduced-scale mock-up. The transfer function of a spring-mass-damper system subjected to a harmonic force in the general coordinates can be written as follows:

$$\left|\frac{q(\omega)}{F(\omega)}\right| = \frac{1}{k}\left[\frac{\omega_n^2}{\sqrt{(\omega_n^2-\omega^2)^2+(2\zeta\omega\omega_n)}}\right] \qquad \text{Eq. 1}$$

where q is the tube displacement at the line of action, ζ is the tube damping ratio in water, k is the tube stiffness. The natural angular frequency of the tube is ω_n, and ω is the angular frequency. In Eq. 1, the fluid force can be estimated by evaluating the system transfer function.

Free decay tests in air and water for a single flexible tube in the array are performed to determine the tube modal parameters, including frequency (f), damping ratio (ζ), and added-mass (m_{added}). The added-mass term is determined from the tube frequency difference between air and water. Figure 9(a) and Figure 9(b) show curve fittings of the experimental results in air and water, respectively, using a one-degree-of-freedom frequency response function (FRF). The added-mass coefficient (C_m) is approximately 0.30.

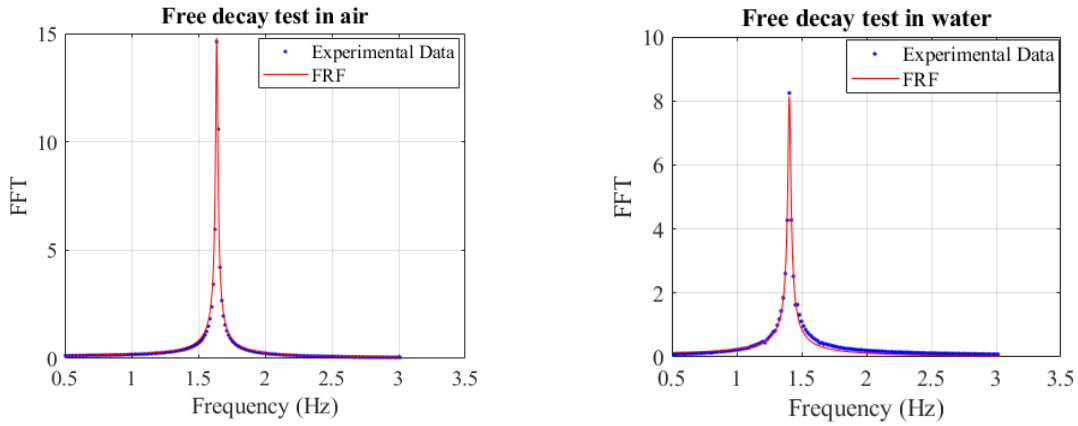


Figure 9. Typical Frequency Response Function (FRF) fit of free vibration decay tests: (a) in air and (b) in water.

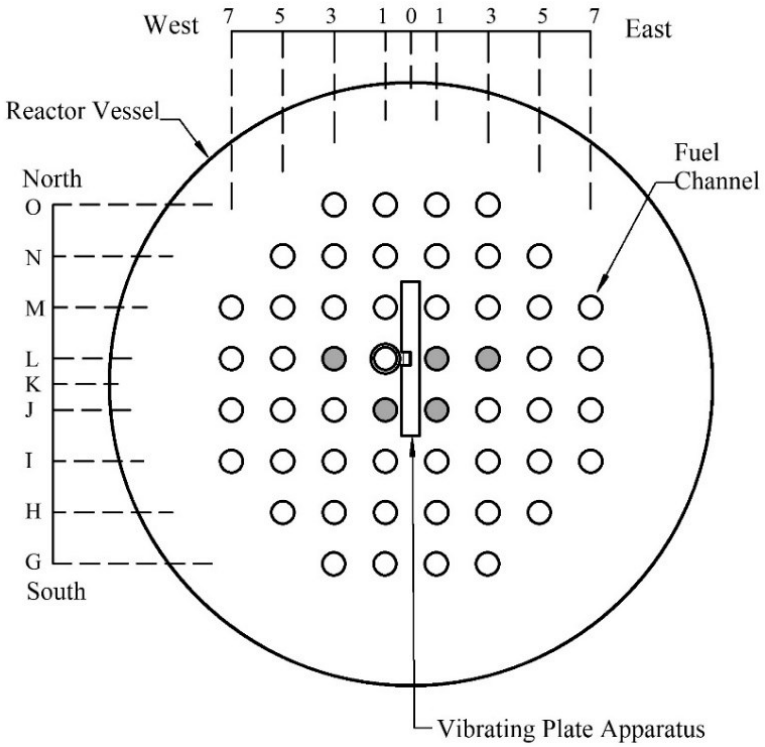
Having defined the modal parameters, the fluid forces are calculated in both the x- and y- directions from the transfer function using the displacement amplitudes from the tube array response (refer to Figure 5 for a sample illustration of the tube array response at 1.30 Hz excitation frequency). The fluid force coefficients are then calculated from the following equations:

$$C_x = \frac{F_x}{\frac{1}{2}\rho(DL)(\omega L_{Vib.})^2} \qquad \text{Eq. 2}$$

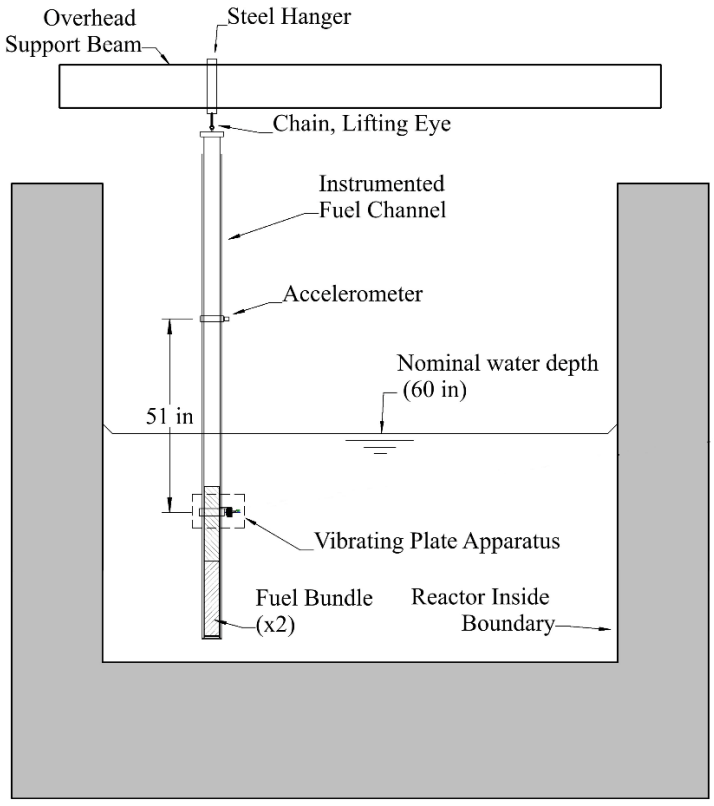
$$C_y = \frac{F_y}{\frac{1}{2}\rho(DL)(\omega L_{Vib.})^2} \qquad \text{Eq. 3}$$

where D is the tube diameter, L is the tube length exposed to water, $L_{Vib.}$ is the vibrating tube displacement at the line of action, ω is the angular excitation frequency, ρ is the fluid density. Since there is no flow, the velocity is determined based on the motion of the oscillating tube. The velocity amplitude is estimated as $\omega L_{Vib.}$, assuming the tubes exhibit simple harmonic motion. Accordingly, the tube velocity is expressed as $\dot{x} = L_{vib}.\omega \cos(\omega t)$.

Scaling the force coefficients on the fuel channels is performed by comparing the layout of the mock-up tube array, as show in Figure 1(b), with the ZED-2 fuel channel array layout, as shown in Figure 10(a). The fluid force coefficients for the five fuel channels surrounding the instrumented fuel channel with the shaker-plate assembly, are highlighted in grey in Figure 10(a). The vibrating plate apparatus is positioned 35.42 inches above the bottom of the fuel channel, as shown in Figure 10(b). Figure 11(a) and 11(b) show the force coefficients calculated in the x- and y- directions, respectively. The force coefficients show an increase with frequency. The increase in the force coefficients with increase in the frequency ratio is due to the forces, F_x and F_y, being normalized with respect to the square of the vibration displacement amplitude ($L_{Vib.}$), which decreases with frequency, as shown in Figure 4.



(a)



(b)

Figure 10. (a) ZED-2 reactor core map, and (b) side view of the vibrating plate apparatus setup.

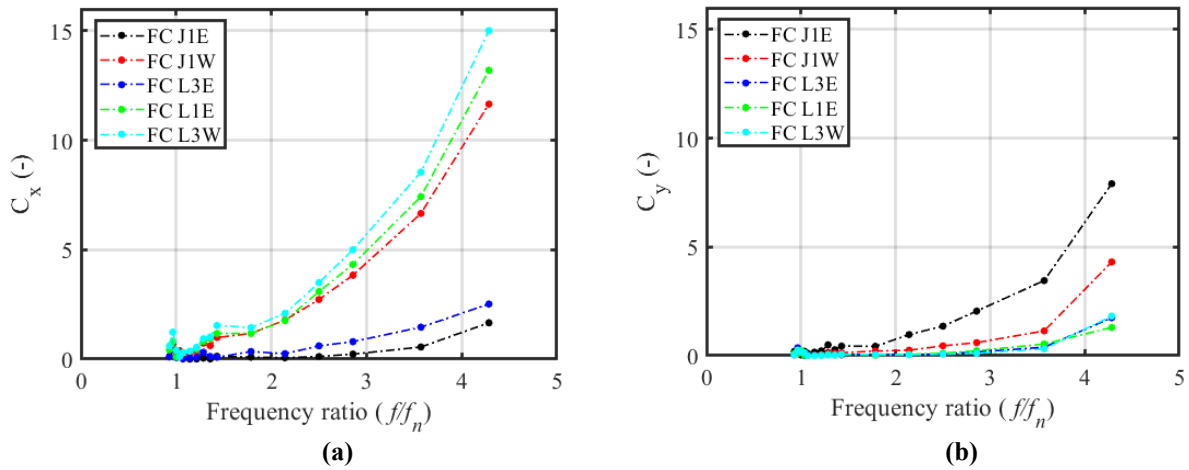


Figure 11. Fluid force coefficients (C_x&C_y) as functions of the frequency ratio (f/f_n) for the five fuel channels, FC J1E, J1W, L3E, L1E, and L3W: (a) C_x and (b) C_y.

Fuel Channel Array Response

Each fuel channel is attached by a stainless-steel chain to a stainless-steel hanger to be suspended in the reactor core. The chain attaches to the centre of the fuel channel. Therefore, the swaying motion of the fuel channel can be represented similar to a compound pendulum [11]. Consider a fuel channel in the array swaying at an angle (θ) due to an external excitation force as shown in Figure 12. The equation of motion of the fuel channel can be written as follows:

$$\sum M_O = \left(\frac{1}{12}M_{Tube}L^2 + M_{Tube}L_{C.G.}^2 + \frac{1}{12}M_{Added}L_{Exposed}^2 + M_{Added}L_{Added}^2\right)\ddot{\theta} = F_{Shaker}L_{Shaker} - M_{Tube}gL_{C.G.}sin\theta - M_{Added}gL_{Added}sin\theta - c_{viscous}L_{C.G.}^2\dot{\theta} - c_{Hinge}L_{C.G.}^2\dot{\theta} \quad \text{Eq. 4}$$

where F_{Shaker} is the external force applied to the fuel channel, L_{Shaker} is the location of the external force, L is the fuel channel length, $L_{C.G.}$ is the location the center of mass of the fuel channel, L_{Added} is the central location of the added mass along the channel, $L_{Exposed}$ is the immersed fuel channel length in water, $c_{viscous}$ is the viscous damping coefficient, c_{Hinge} is the friction damping coefficient. The damping caused by frictional forces between the chain and the pin is considered negligible in the dynamic analysis of the fuel channel, relative to the viscous damping effects.

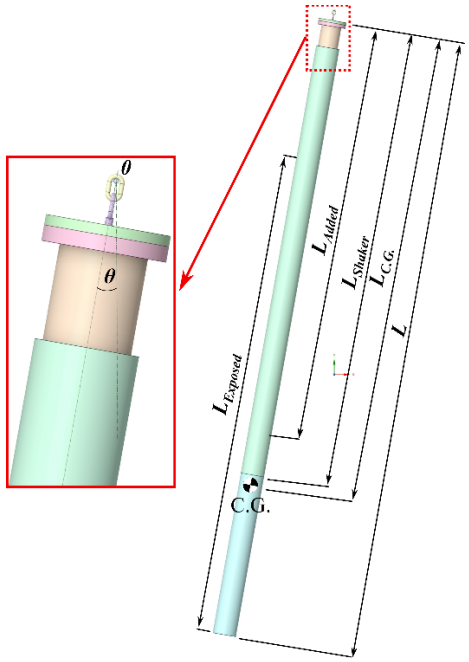
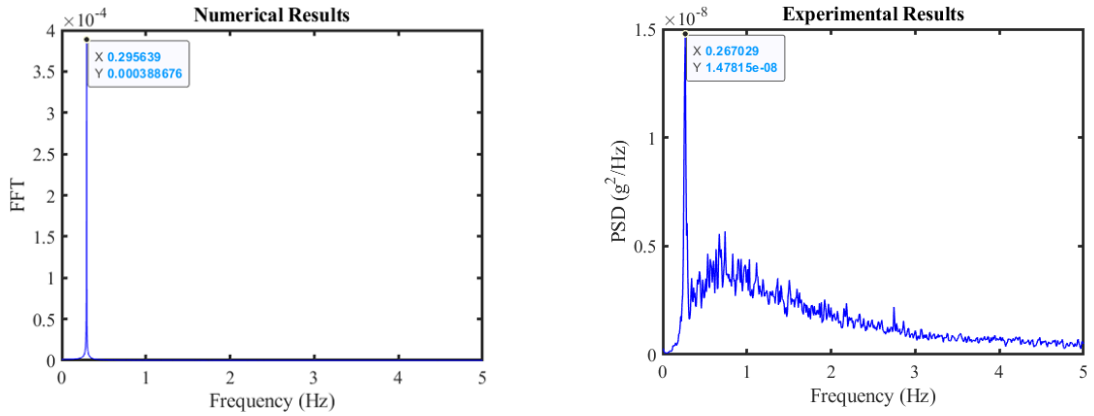


Figure 12. Schematic drawing showing the swing angle of the fuel channel and the modelling parameters of the fuel channel.

For small fuel channel vibrations and ignoring the friction damping term, Eq. 4 can be written as follows:

$$\sum M_O = \left(\frac{1}{12}M_{Tube}L^2 + M_{Tube}L_{C.G.}^2 + \frac{1}{12}M_{Added}L_{Exposed}^2 + M_{Added}L_{Added}^2\right)\ddot{\theta} = F_{Shaker}L_{Shaker} - M_{Tube}gL_{C.G.}\theta - M_{Added}gL_{Added}\theta - c_{viscous}L_{C.G.}^2\dot{\theta} \quad \text{Eq. 5}$$

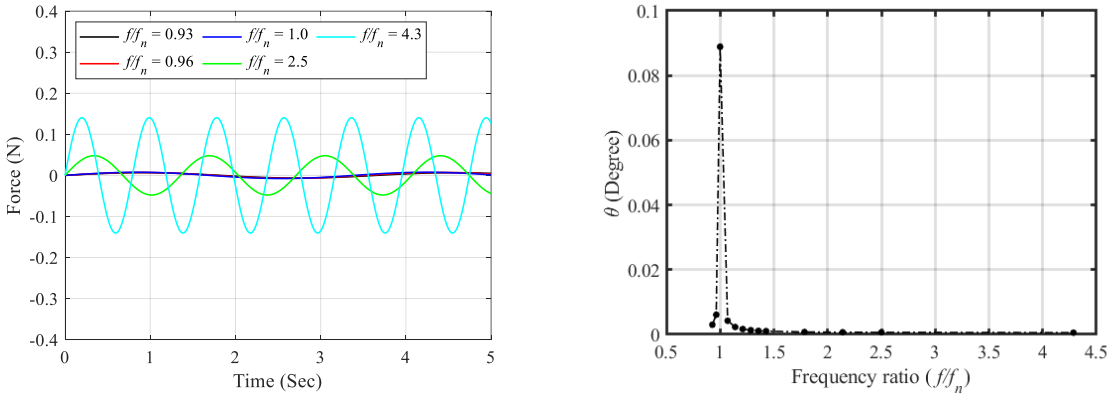
Time domain simulations are conducted to determine the swaying angle (θ) of the instrumented fuel channel with the shaker-plate assembly. The natural frequency of the fuel channel (f_n) is initially calculated from the coefficients of $\ddot{\theta}$ and θ as $f_n = \frac{1}{2\pi}\sqrt{\frac{Coeff.\ of\ \theta}{Coeff.\ of\ \ddot{\theta}}}$. The Fast Fourier Transform (FFT) of the numerical results at f_n is presented in Figure 13(a). To validate the developed model, it is necessary to measure the natural frequency of the fuel channel. This can be achieved through free vibration decay tests conducted in ZED-2, where the fuel channel is initially displaced from its equilibrium position and allowed to swing freely, enabling the characterization of its dynamic response. However, performing this test within the ZED-2 reactor is impractical, as filling the reactor with heavy water makes it operational. The flow of water during the filling process around the fuel channels may induce low-level vibrations. An accelerometer is installed on one of the fuel channels, and the signal is recorded during the reactor's filling process. Figure 13(b) presents the Power Spectral Density (PSD) of the recorded data, which shows a peak at 0.267 Hz. The model results are in good agreement with the experimental results with an error of 10.5%.



(a) **(b)**

Figure 13. (a) Fast Fourier transform (FFT) spectrum of the numerical results for the fuel channel vibration, and (b) Power Spectral Density (PSD) of the experimental results for the fuel channel vibration.

Figure 14(a) shows the shaker force as a function of the frequency ratio (f/f_n), where f_n is the natural frequency of the fuel channel, and f is the excitation frequency. Figure 14(b) shows the responses of the fuel channel calculated over a range of frequency ratios, f/f_n, covering from 0.93 to 4.3. At f/f_n = 1.00, the fuel channel swings at an angle of 0.09°, resulting in a displacement of 3.9 mm at the shaker location. At $f/f_n \geq 1.07$, the fuel channel response decreases to near zero, as observed in the ZED-2 mock-up experiments (see Figure 8). The responses of the instrumented fuel channel with the shaker are used to estimate the cross-coupling forces on the surrounding fuel channels using the mock-up fluid force coefficients. The swing angles of the five fuel channels around the instrumented fuel channel are calculated by solving Eq. 5, where the term $F_{Shaker}L_{Shaker}$ is replaced with the moment generated by the cross-coupling forces. Figure 15 shows the amplitude ratios between the surrounding fuel channels and the instrumented fuel channel in the x- and y- directions as functions of the frequency ratio (f/f_n). The largest amplitude ratio ($\theta/\theta_{Exciter}$) occurs at resonance ($f/f_n = 1.00$), reaching a peak $\theta/\theta_{Exciter}$ of 0.7 in the excitation direction (i.e. x-direction) and 0.4 in the y-direction. The $\theta/\theta_{Exciter}$ linearly decreases beyond $f/f_n = 1.00$, until it reaches zero at $f/f_n \geq 2.50$.



(a) **(b)**

Figure 14. (a) Inertia forces produced by the shaker at different frequency ratios (f/f_n) and (b) the responses of the instrumented fuel channel.

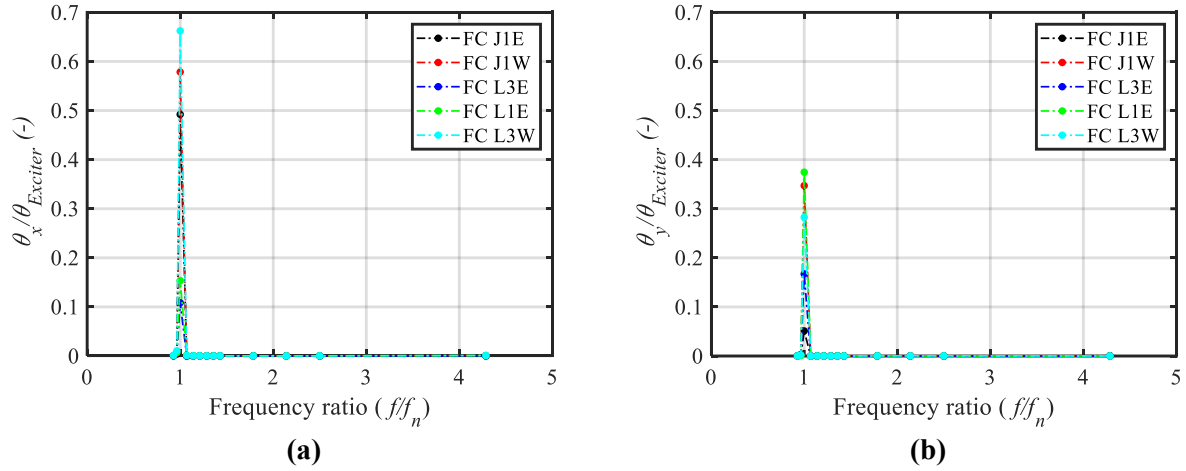


Figure 15. Amplitude ratios between the instrumented fuel channel with the vibrating plate and its surrounding fuel channels in the x- and y- directions as functions of the frequency ratio (f/f_n): (a) $\theta_x/\theta_{Exciter}$ and (b) $\theta_y/\theta_{Exciter}$.

CONCLUSION

The primary aim of this work is to investigate the safety consequences of attaching a vibrating plate to a fuel channel inside the ZED-2 reactor. A reduced scale mock-up of the ZED-2 reactor was designed and built at CNL's Chalk River Laboratories to measure the cross-coupling responses in a tube array due to a vibrating tube. The 5 x 5 square tube array was designed to mimic a part of the fuel channel array in the ZED-2 reactor. A group of five tubes surrounding the vibrating tube was instrumented with strain gauges to measure their responses at different excitation frequencies.

The mock-up experiments showed that the neighboring tubes are strongly coupled with the vibrating tube when it vibrates at frequencies near the resonant frequency of the individual tubes in the mock-up tube array in water. The three nearest tubes around the vibrating tube had the largest amplitudes in the array due to the strong hydrodynamic coupling. At resonance, the amplitude ratio between the surrounding tubes and the vibrating tube ($A/A_{Vibrating\ Tube}$) was 0.25 in the excitation (x) direction and 0.15 in the y-direction.

Free decay tests in air and water are conducted to determine the fluid-added-mass and the damping ratio of the mock-up tube. These parameters were used to determine the transfer function between the fluid force and the tube response. Hence, the measured responses from the mock-up tests were employed to estimate the fluid forces applied to the mock-up tubes based on the transfer function. Moreover, the fluid force coefficients were calculated as functions of the frequency and displacement of the vibrating tube.

The responses of the ZED-2 fuel channels were computed using the fluid force coefficients obtained from the mock-up experiments. The analysis showed that the largest amplitude ratio ($\theta/\theta_{Exciter}$) obtained at the resonant frequency is 0.7. This ratio is used as a safety limit to design the ZED-2 apparatus.

ACKNOWLEDGEMENTS

This work was supported by Atomic Energy of Canada Limited's Federal Nuclear Science & Technology Work Plan.

REFERENCES

[1] Pázsit, I., & Demaziere, C., Noise techniques in nuclear systems, In Handbook of Nuclear Engineering, 2010.

[2] Fry, D. N., Kryter, R. C., & Robinson, J. C., "Analysis of neutron-density oscillations resulting from core barrel motion in the Palisades nuclear power plant," Oak Ridge National Lab, 1974.

[3] M. Antonopoulos-Domis, "Reactivity and neutron density noise excited by random rod vibration," *Annals of Nuclear Energy,* vol. 3, pp. 451-459, 1976.

[4] Vidal-Ferràndiz, A., Ginestar, D., Carreño, A., Verdú, G., Dokhane, A., Verma, V., & Vinai, P., "Modelling and simulations of reactor neutron noise induced by mechanical vibrations," *Annals of Nuclear Energy,* vol. 177, 2022.

[5] Pázsit, I., & Glöckler, O., "On the neutron noise diagnostics of pressurized water reactor control rod vibrations. I. Periodic vibrations," *Nuclear Science and Engineering,* vol. 85, pp. 167-177, 1983.

[6] Pázsit, I., & Glöckler, O., "On the neutron noise diagnostics of pressurized water reactor control rod vibrations II. Stochastic vibrations," *Nuclear Science and Engineering,* vol. 88, pp. 77-87, 1984.

[7] Yu, I.W., "Determination of hydrodynamic mass using a general purpose finite element structural code," *ASME Paper No. 80-C2/PVP-117,* 1980.

[8] Yu, I.W. and Vanburen, W., "Dynamic analyses of a tube in a fluid," *IASMiRT,* 1983.

[9] Moretti, P.M. and Lowery, R.L., "Hydrodynamic inertia coefficients for a tube surrounded by rigid tubes," *Journal of Pressure Vessel Technology,* 1976.

[10] Thie, J. A., "Reactor-noise monitoring for malfunctions," *Reactor Technol. 14: No. 4, 354-65 (Winter 1971-1972),* 1972.

[11] Inman, D. J. and Singh, R. C., Engineering vibration, 1994: Prentice Hall Englewood Cliffs, NJ.