CORTEX

Core monitoring techniques and experimental validation and demonstration

Understanding the neutron noise induced by fuel assembly vibrations in linear theory

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Introduction

- Special emphasis in CORTEX on fuel assembly vibrations
- Different patterns noticed in the spatial dependence of the induced neutron noise
- Purpose of this work:

  To explain the spatial structure of the neutron noise for fuel assembly vibrations

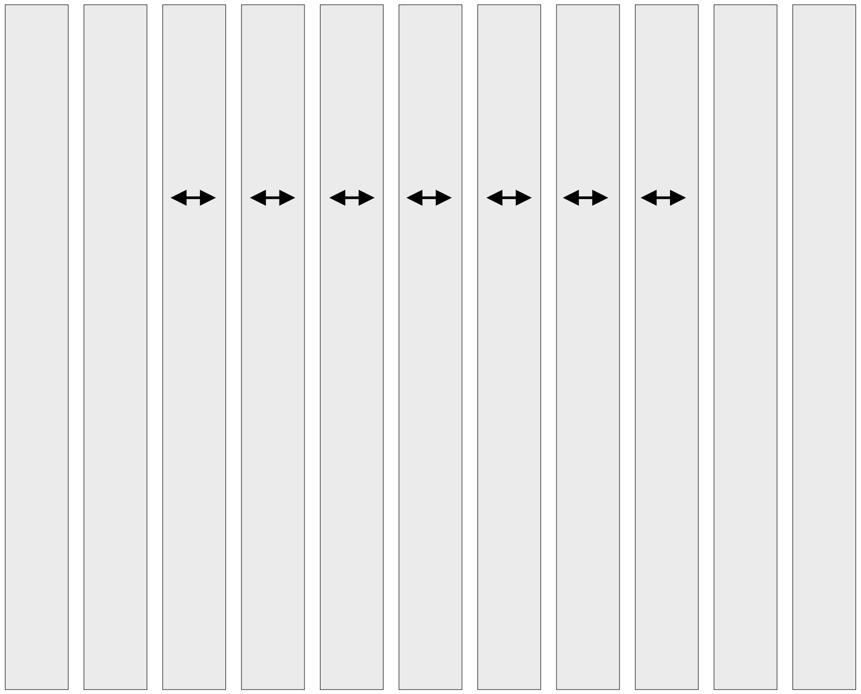
Introduction

- Plan of the presentation:
  - Representation of vibrating interfaces
  - System considered
  - Understanding the induced neutron noise
  - Analysis of the noise source
  - Analysis of the induced neutron noise
  - Conclusions

Representation of vibrating interfaces

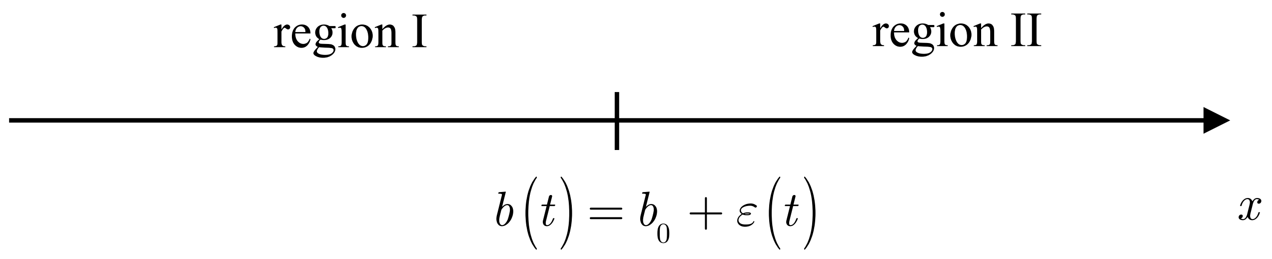
Representation of vibrating interfaces

- Fuel assembly vibrations = displacement of the boundaries between homogeneous regions



Representation of vibrating interfaces

- Illustration on a moving interface between two homogeneous regions:



➢ Static cross-section representation:

$$\Sigma_{\alpha,0}(x) = \left[1 - \mathrm{H}(x - b_0)\right]\Sigma_{\alpha,I} + \mathrm{H}(x - b_0)\Sigma_{\alpha,II}$$

➢ Dynamic cross-section representation:

$$\delta\Sigma_{\alpha}(x,t) = -\Delta\Sigma_{\alpha}\mathrm{H}(x - b_0) + \Delta\Sigma_{\alpha}\mathrm{H}(x - b_0 - \varepsilon(t))$$

with

$$\Delta\Sigma_{\alpha} = \Sigma_{\alpha,II} - \Sigma_{\alpha,I}$$

Representation of vibrating interfaces

- Illustration on a moving interface between two homogeneous regions:

  For $\varepsilon(t) = d\sin(\omega_0 t)$ and using the model of Rouchon and Sanchez*, one obtains in the frequency domain:

$$\Sigma_\alpha(x,\omega) = -\text{sign}\left[\tau(x)\right] \times \Delta\Sigma_\alpha \times \left[\pi - 2\omega_0 \left|\tau(x)\right|\right] \times \delta(\omega)$$

$$+\sum_{k=-\infty}^{+\infty} \frac{2i\Delta\Sigma_\alpha}{2k+1} \cos\left[\left(2k+1\right)\omega_0 \tau(x)\right] \times \delta\left[\omega - \left(2k+1\right)\omega_0\right] + \sum_{\substack{k=-\infty \\ k\neq 0}}^{+\infty} \frac{2\Delta\Sigma_\alpha}{2k} \sin\left[2k\omega_0 \tau(x)\right] \times \delta\left[\omega - 2k\omega_0\right]$$

with $\tau(x) = \frac{1}{\omega_0} \arcsin\left(\frac{x-b_0}{d}\right)$ and for $x \in \left[b_0 - d; b_0 + d\right]$

➢ Several eigenfrequencies excited

*Rouchon A. and Sanchez R., "Analysis of vibration-induced neutron noise using one-dimension noise diffusion theory," Proc. Int. Congress on Advances in Nuclear Power Plants (ICAPP2015), Nice, France, May 3-5, 2015 (2015).

System considered

System considered

- One-group diffusion theory
- Frequency domain
- Linear theory
- No thermal-hydraulic feedback
- Three-region system of size 3 m with zero flux boundary conditions
- Inner region of size 1 cm moving with $d = 0.5$ cm and $\omega_0 / 2\pi = 1$ Hz
- Effect of the noise source estimated:
  - Numerically using CORE SIM (a modified version)
  - Semi-analytically using the Green's function technique (see paper – purpose: to verify the correctness of the CORE SIM solution)

Understanding the induced neutron noise

Understanding the induced neutron noise

- Point-kinetic component of the neutron noise:

  Using the factorization:

$$\phi\left(\mathbf{r},t\right)=P\left(t\right)\cdot\psi\left(\mathbf{r},t\right)$$

  with

  $P\left(t\right)$ amplitude factor

  $\psi\left(\mathbf{r},t\right)$ shape function

  such that

$$\frac{\partial}{\partial t}\int\phi_0\left(\mathbf{r}\right)\psi\left(\mathbf{r},t\right)d^3\mathbf{r}=0$$

Understanding the induced neutron noise

- Point-kinetic component of the neutron noise:

  One obtains in first order:

$$\delta\phi\left(\mathbf{r},t\right)=\delta P\left(t\right)\phi_{0}\left(\mathbf{r}\right)+\delta\psi\left(\mathbf{r},t\right)$$

  where one assumed:

$$P_{0}=1$$

$$\psi\left(\mathbf{r},t=0\right)=\phi_{0}\left(\mathbf{r}\right)$$

  - Point-kinetic response: $\delta P\left(t\right)\phi_{0}\left(\mathbf{r}\right)$
  - "Space-dependent" response: $\delta\psi\left(\mathbf{r},t\right)$

Understanding the induced neutron noise

- Point-kinetic component of the neutron noise:

  The fluctuations of the amplitude factor are further given, in the frequency domain, as:

$$\delta P(\omega) = G_0(\omega)\,\delta\rho(\omega)$$

with

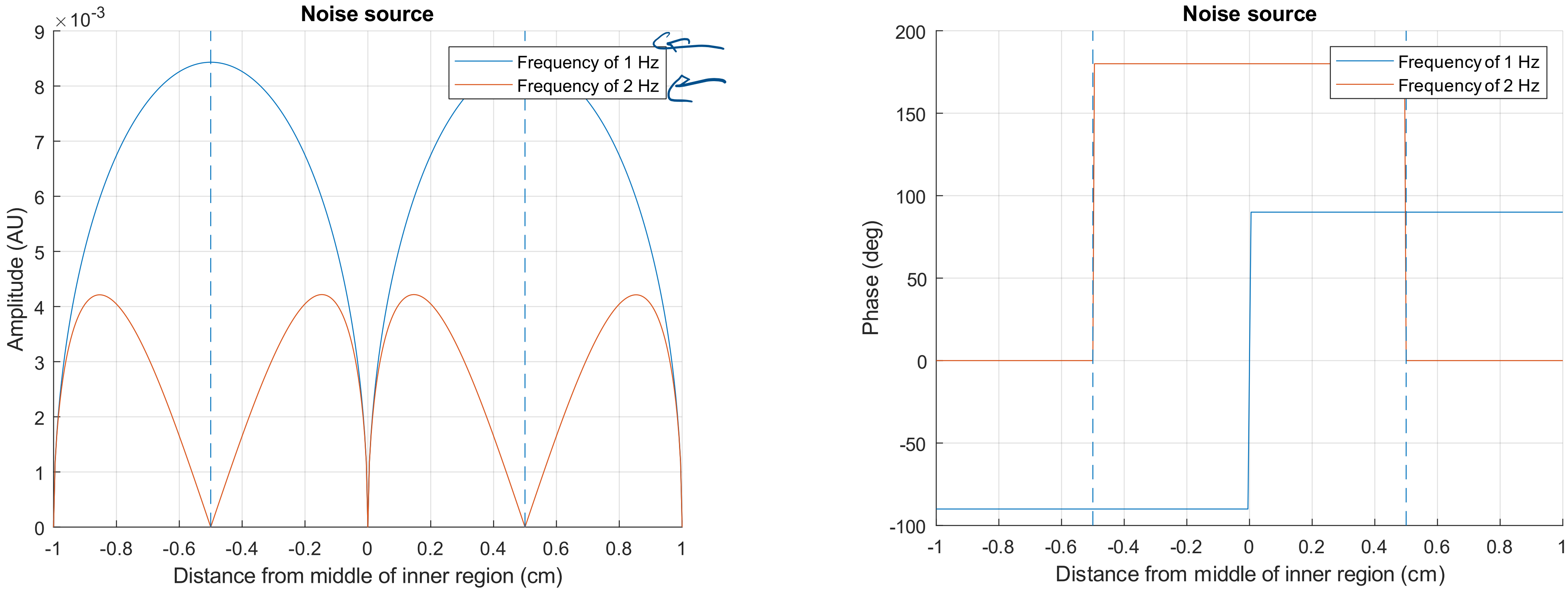
$$G_0(\omega) = \frac{1}{i\omega\left(\Lambda_0 + \dfrac{\beta}{i\omega + \lambda}\right)}$$

zero-power reactor transfer function

(better name: *point-kinetic* zero-power reactor transfer function)

Analysis of the noise source

Analysis of the noise source



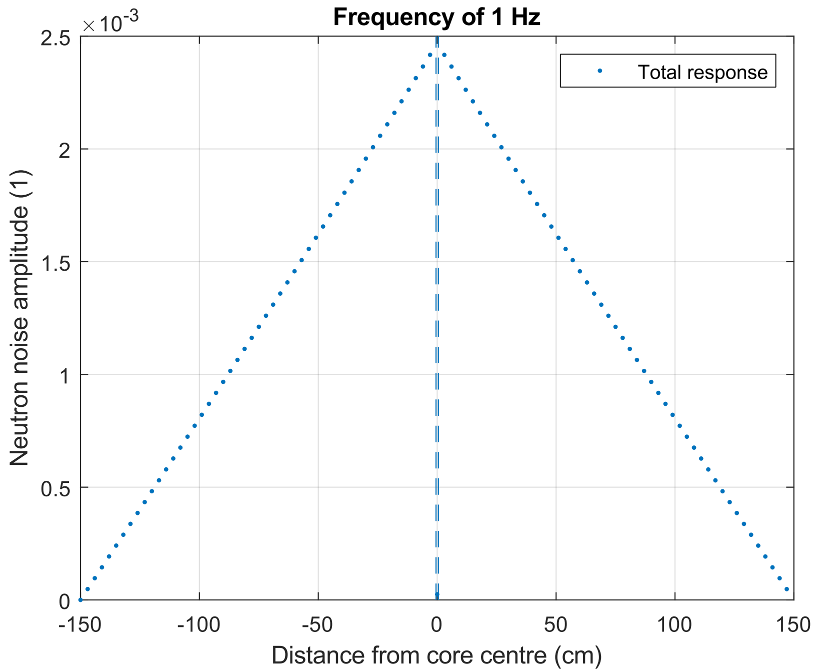
Amplitude (left figure) and phase (right figure) of the noise source at 1 Hz and 2 Hz in the case of an inner region moving in relation to two outer regions in a large reactor

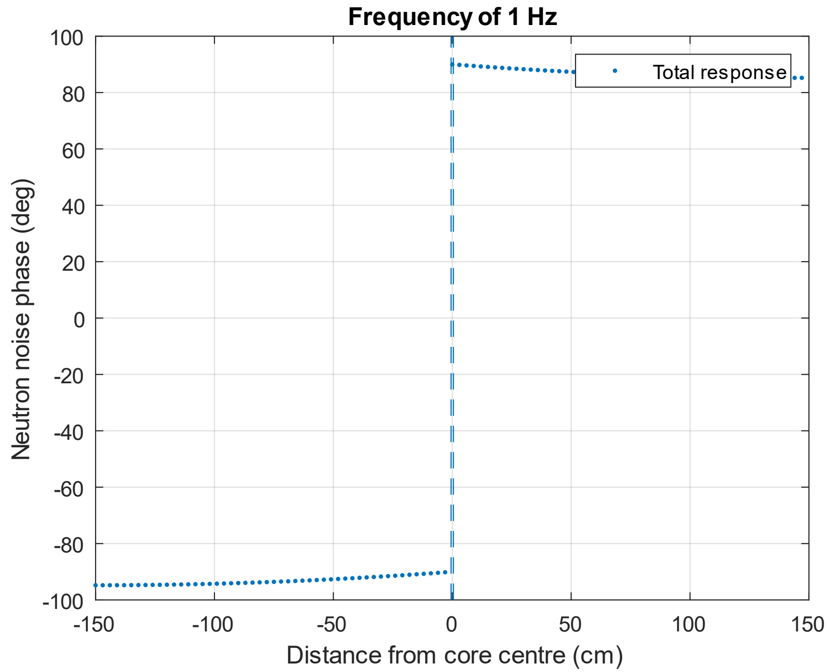
Analysis of the noise source

- At 1 Hz:
  - Anti-symmetrical (out-of-phase) perturbations <u>around the centre of the moving region</u>
    - ➢ Each moving boundary expected to give a point-kinetic response of varying amplitude
    - ➢ Those point-kinetic responses are expected to be out-of-phase and compensate each other to some extent
- At 2 Hz:
  - Anti-symmetrical (out-of-phase) perturbations <u>around the respective boundaries</u>
    - ➢ Each side of the moving boundary expected to give a point-kinetic response of varying amplitude
    - ➢ Those point-kinetic responses are expected to be out-of-phase and compensate each other to some extent
  - Symmetrical perturbation <u>around the centre of the moving region</u>
    - ➢ In-phase contributions to the induced neutron noise

Analysis of the induced neutron noise

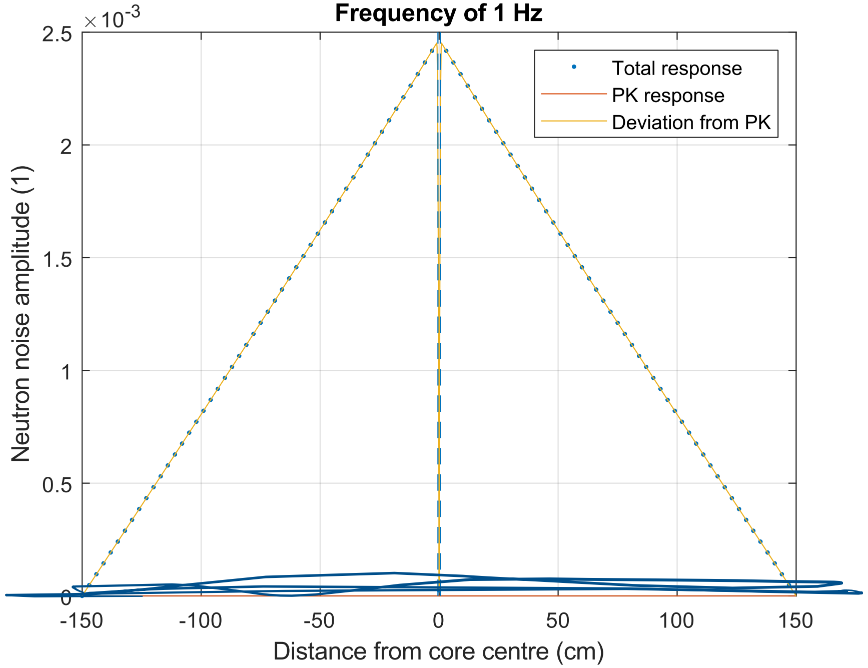
Analysis of the induced neutron noise

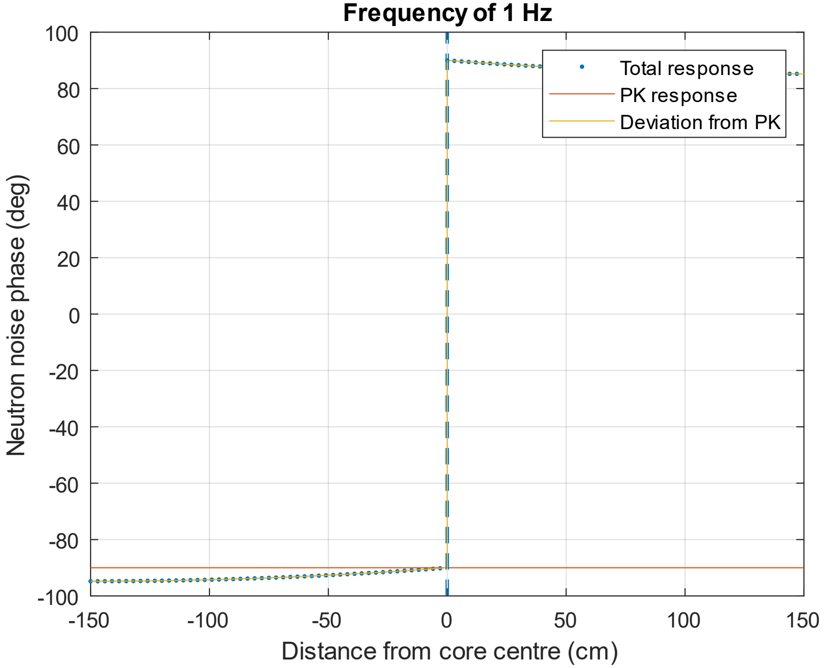




Amplitude (left figure) and phase (right figure) of the induced neutron noise at **1 Hz** for a **central moving region** (induced neutron noise in blue, its point-kinetic component in red and its deviation from point-kinetics in yellow)

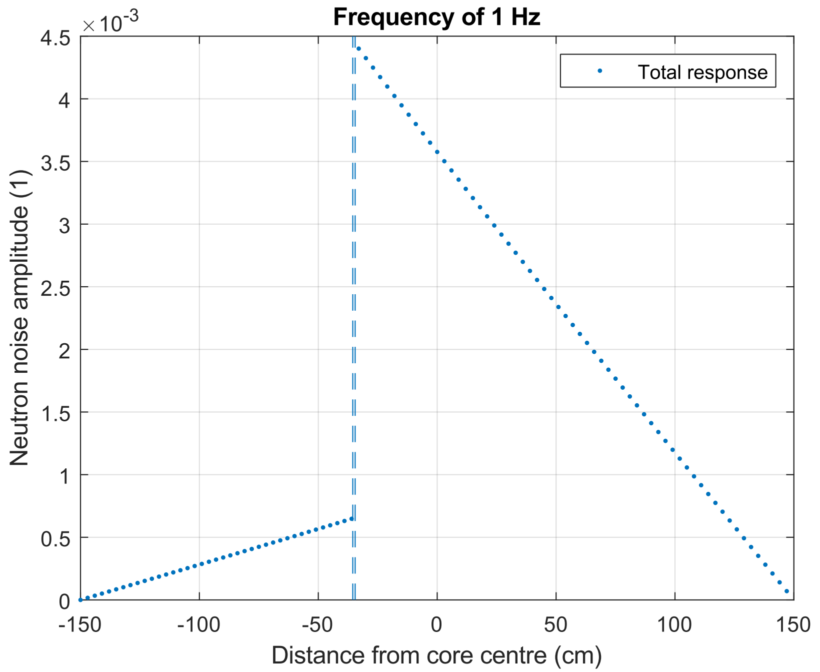
Analysis of the induced neutron noise

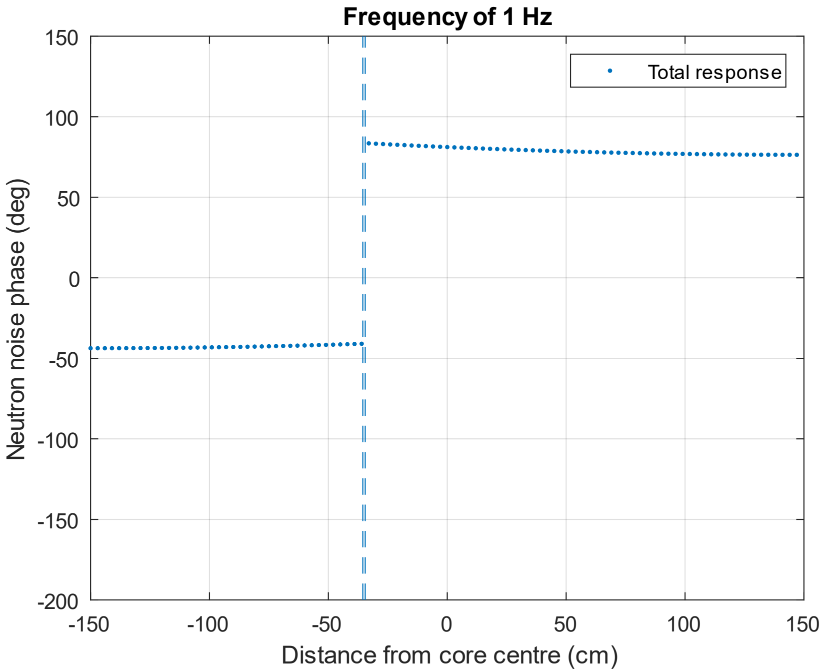




Amplitude (left figure) and phase (right figure) of the induced neutron noise at **1 Hz** for a **central moving region**
(induced neutron noise in blue, its point-kinetic component in red and its deviation from point-kinetics in yellow)

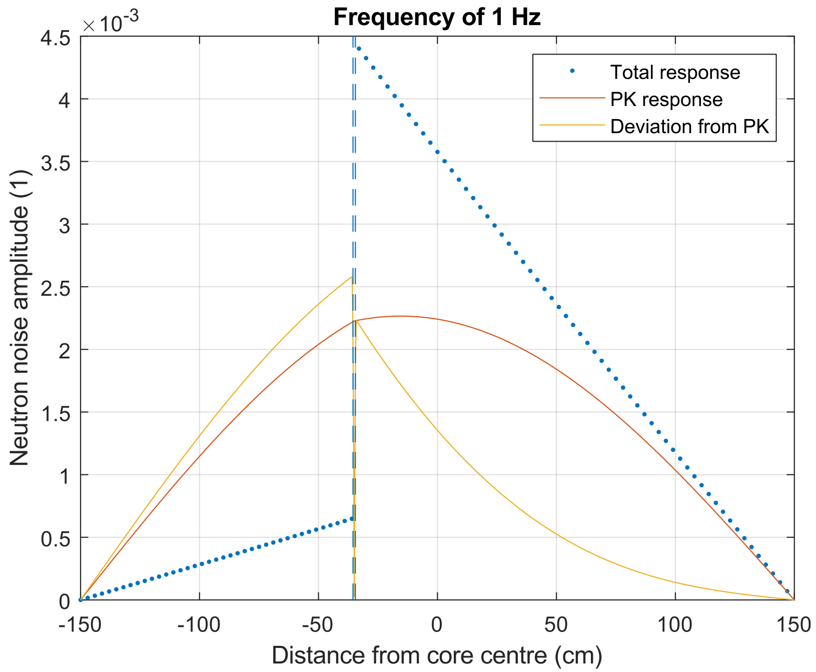
Analysis of the induced neutron noise

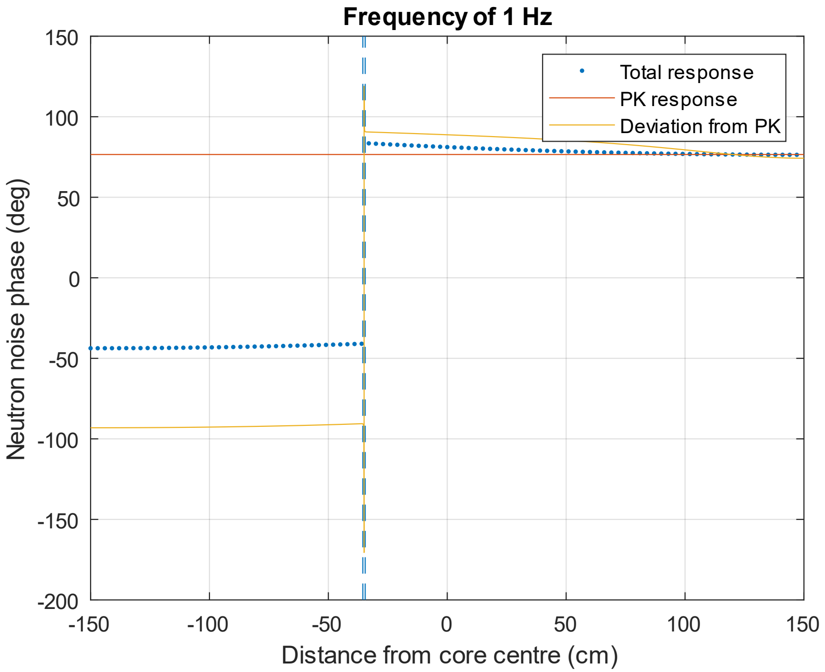




Amplitude (left figure) and phase (right figure) of the induced neutron noise at **1 Hz** for a **peripheral moving region** (induced neutron noise in blue, its point-kinetic component in red and its deviation from point-kinetics in yellow)

Analysis of the induced neutron noise



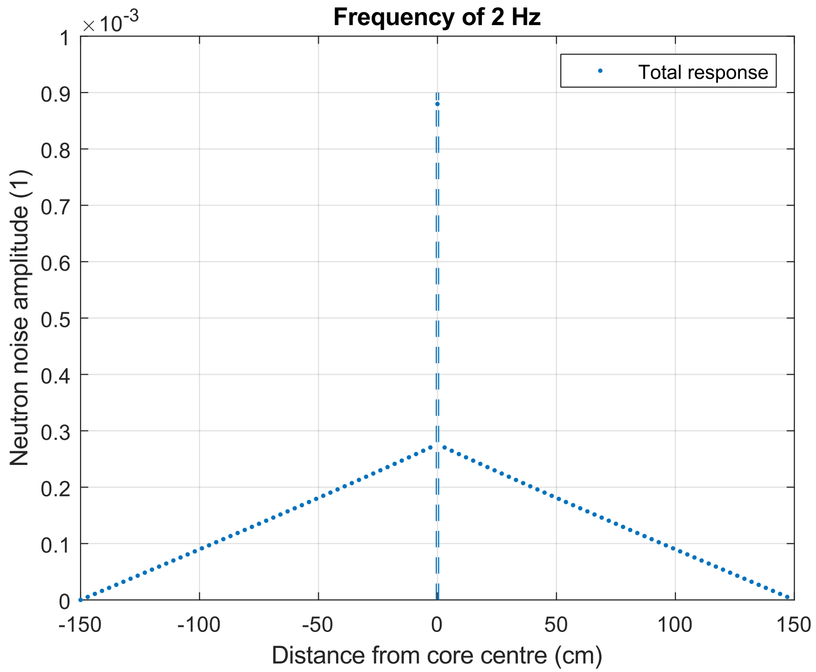


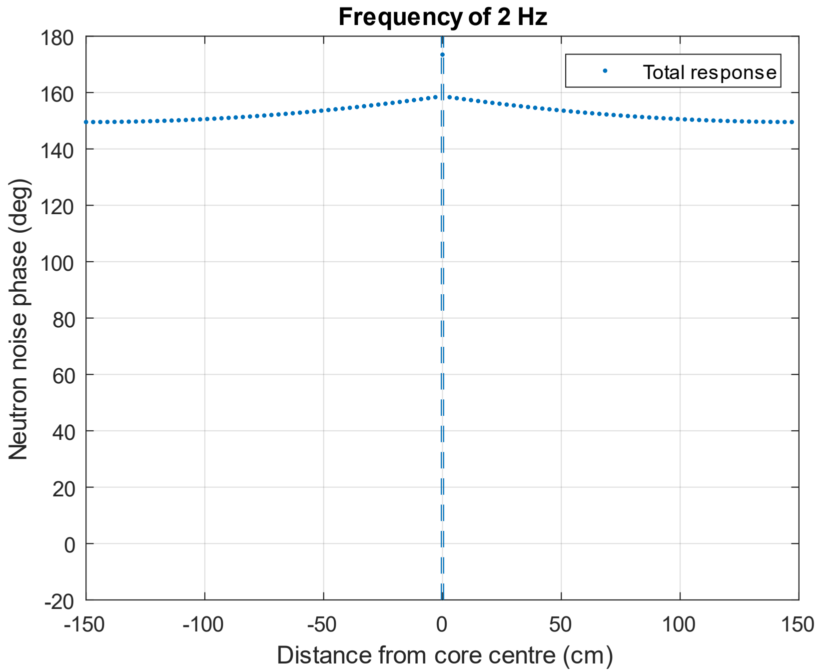
Amplitude (left figure) and phase (right figure) of the induced neutron noise at **1 Hz** for a **peripheral moving region**
(induced neutron noise in blue, its point-kinetic component in red and its deviation from point-kinetics in yellow)

Analysis of the induced neutron noise

- At 1 Hz: compensation of the resulting induced neutron noise between the two moving boundaries
  - ➢For a **central** moving region: perfect compensation of the point-kinetic responses → leading to pure non-point-kinetic behaviour and a small amplitude of the neutron noise
  - ➢For a **peripheral** moving region: non perfect compensation of the point-kinetic responses → leading to a significant point-kinetic response and a larger amplitude of the neutron noise

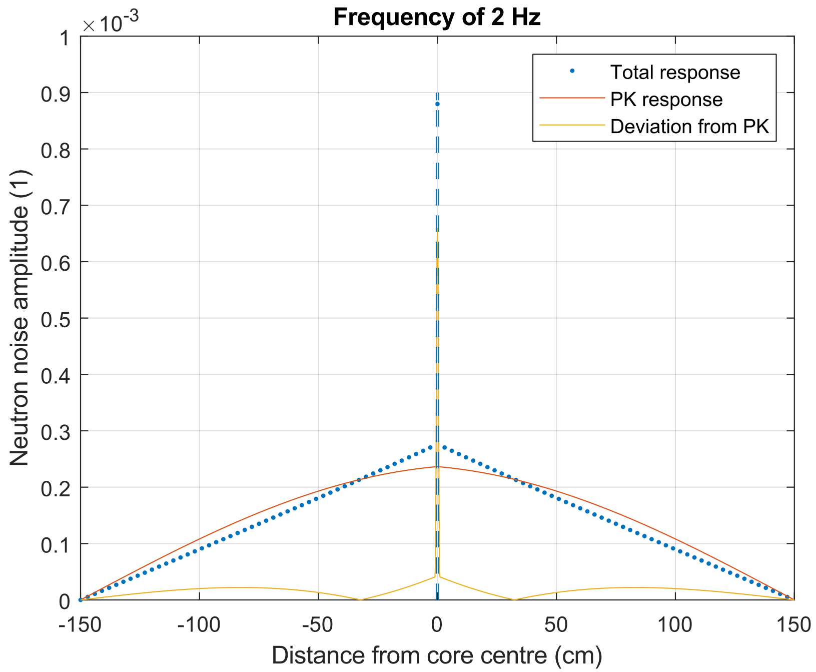
Analysis of the induced neutron noise

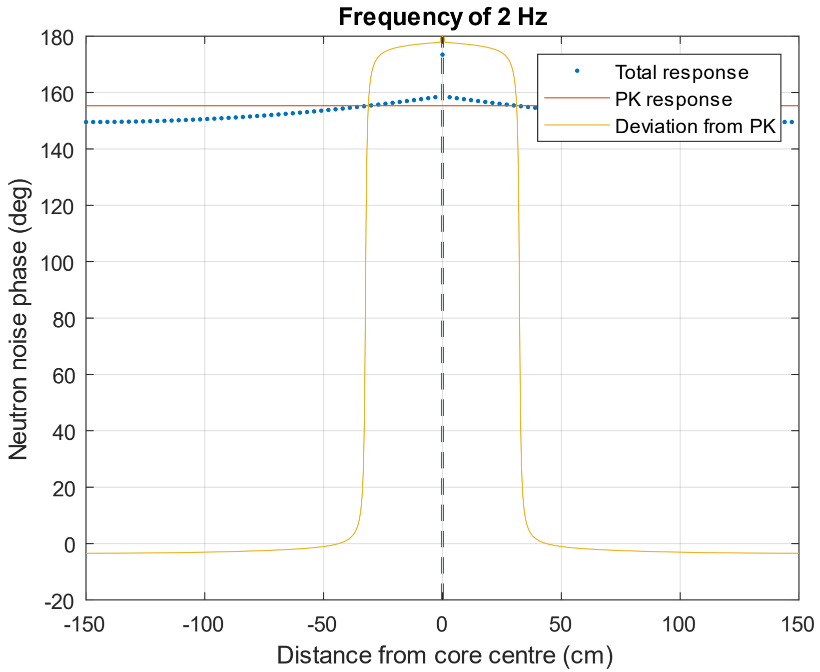




Amplitude (left figure) and phase (right figure) of the induced neutron noise at **2 Hz** for a **central moving region**
(induced neutron noise in blue, its point-kinetic component in red and its deviation from point-kinetics in yellow)

Analysis of the induced neutron noise





Amplitude (left figure) and phase (right figure) of the induced neutron noise at **2 Hz** for a **central moving region**
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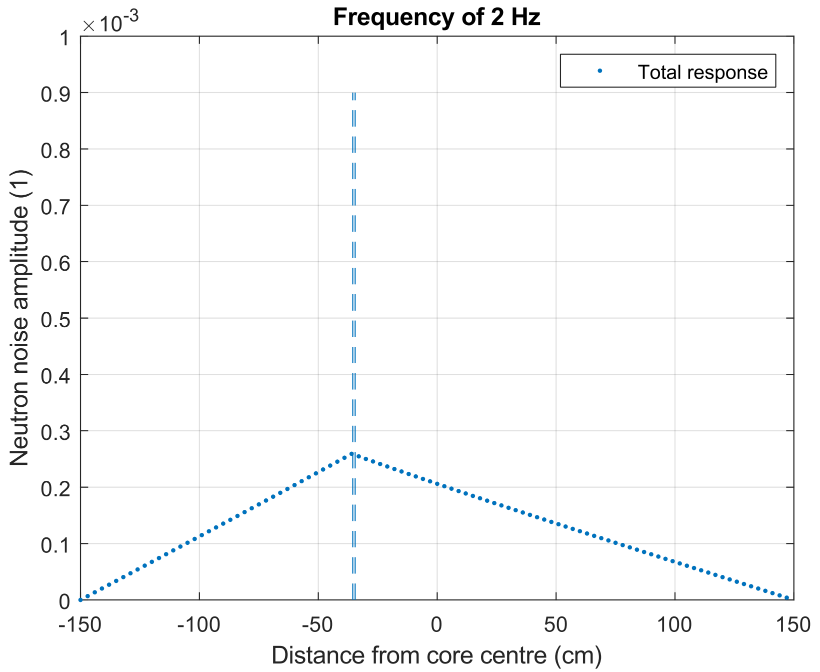
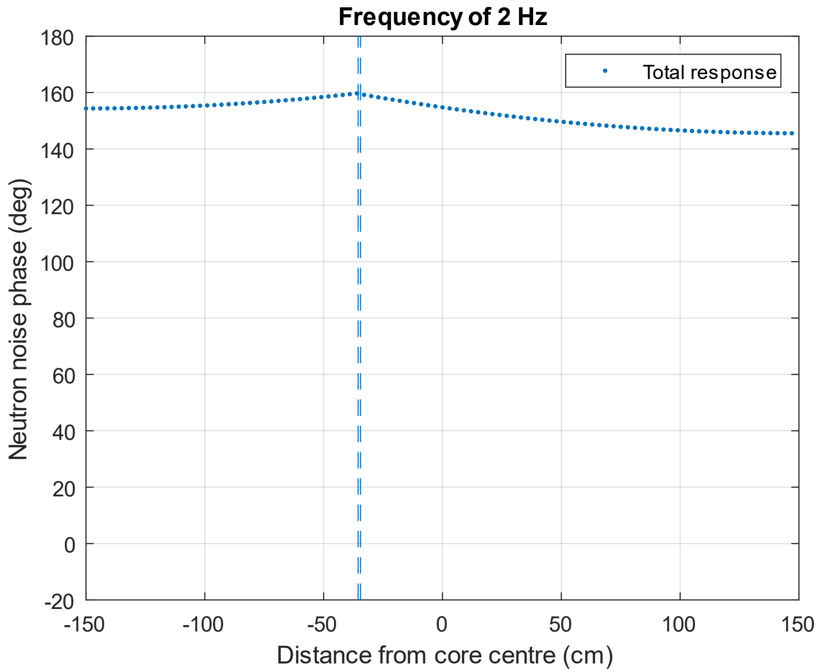
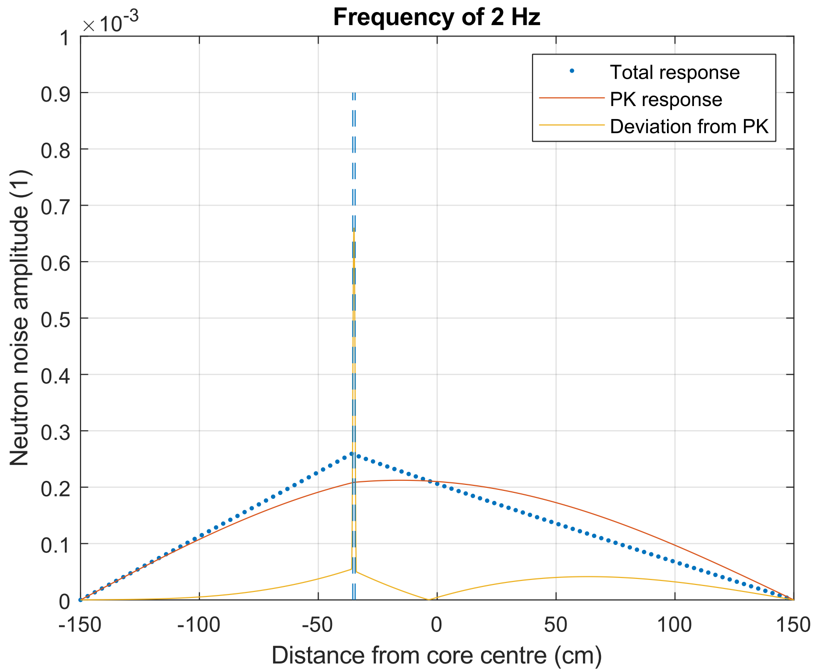
Analysis of the induced neutron noise

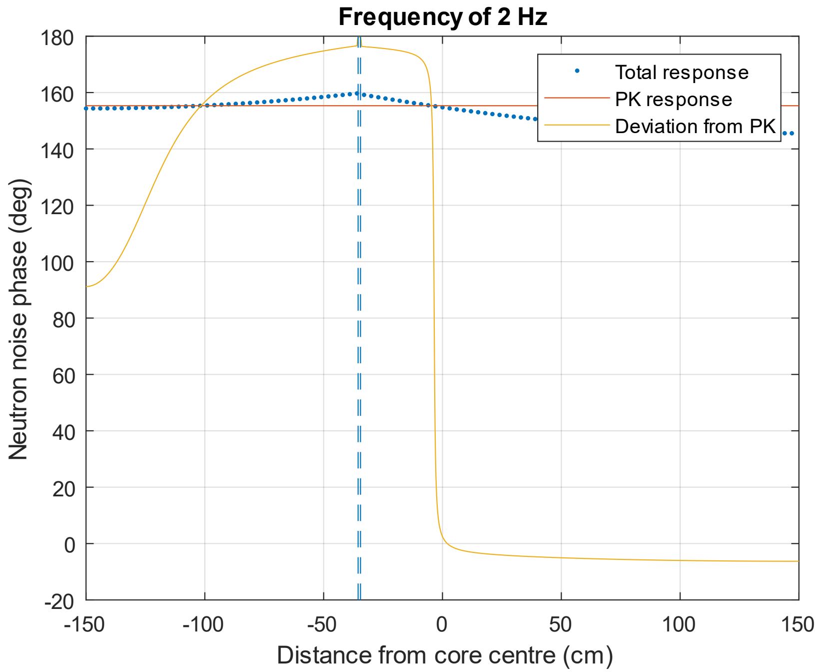




Amplitude (left figure) and phase (right figure) of the induced neutron noise at **2 Hz** for a **peripheral moving region**
(induced neutron noise in blue, its point-kinetic component in red and its deviation from point-kinetics in yellow)

Analysis of the induced neutron noise





Amplitude (left figure) and phase (right figure) of the induced neutron noise at **2 Hz** for a **peripheral moving region**
(induced neutron noise in blue, its point-kinetic component in red and its deviation from point-kinetics in yellow)

Analysis of the induced neutron noise

- At 2 Hz: significant point-kinetic responses
  - ➢For **central** moving region:
    - For each moving boundary: point-kinetic responses cancelling each other to some extent $\rightarrow$ leading to deviation from point-kinetics
    - Combining the two moving boundaries: cancellation of the deviation from point-kinetics above which are out-of-phase $\rightarrow$ re-establishing an apparent point-kinetic behaviour
  - ➢For **peripheral** moving region:
    - For each moving boundary: non-negligible point-kinetic responses not cancelling each other $\rightarrow$ leading to point-kinetic response
    - Combining the two moving boundaries: subtraction of two point-kinetic responses which are out-of-phase $\rightarrow$ overall point-kinetic response

Conclusions

Conclusions

- Vibrations of structures lead to an intricate combination of point-kinetic responses and space-dependent responses
- Different responses obtained depending on:
  - The position of the moving regions
  - The harmonics being considered
  - The gradient of the static flux
- Same qualitative behaviour observed in 2-group theory with explicit modelling of all pins

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