Determination of Delayed Neutrons Source in the Frequency Domain Based on in-pile Oscillation Measurements

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Abstract

A method for determining delayed neutrons source in the frequency domain based on measuring power oscillations in a non-critical reactor is presented. This method is unique in the sense that the delayed neutrons source is derived from the dynamic behavior of the reactor, which serves as the measurement system. An algorithm for analyzing power oscillation measurements was formulated, which avoids the need for a multi-parameter non-linear fit process used by other methods. Using this algorithm results of two sets of measurements performed in IRR-I & IRR-II (Israeli Research Reactors I & II) are presented. The agreement between measured values from both reactors and calculated values based on Keepin (and JENDL-3.3) group parameters is very good.

KEYWORDS: ***Delayed Neutrons, In-Pile Measurements, IRR-I, IRR-II***

1. Introduction

Describing the time evolution of a non-critical reactor [1] requires the knowledge of the delayed neutrons fraction [2] - β (or more precisely β_{eff}, which accounts for the delayed neutrons spectral properties) and their emission rate as a function of the time elapsed since the fission event. It is common to approximate the emission rate using the delayed neutrons group parameters [2] – a set of effective decay constants of the delayed neutrons precursors, λ_j, and delayed neutrons fractions in each group, β_j. The Normalized Emission Rate (NER) as a function of the time elapsed since the fission event, t, is expressed by the group parameters as follows:

$$g(t) = \theta(t)\frac{1}{\beta}\sum_j \beta_j \lambda_j e^{-\lambda_j t} , \qquad (1)$$

where $\theta(t)$ is the Heaviside step function.

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As a consequence of their importance to nuclear reactor theory, the results of more than a hundred measurements were published throughout the years (for a thorough review consider Ref. 3), with the purpose of determining delayed neutrons group parameters. The analysis of these measurements, the majority of which are out-of-pile measurements, resulted in various published sets for the group parameters [4-9]. Yet, as was clearly demonstrated by Spriggs & Campbell [3], there are significant discrepancies between the NER time dependence predicted by different sets. These discrepancies, often exceeding the uncertainties reported by each individual set, lead to meaningful differences in measured reactivity derived from kinetic experiments [10, 11], as well as to substantial differences in time evolution predictions in reactor-kinetics calculations [12].

Only a few in-pile kinetic measurements aimed to determine delayed neutrons group parameters were published [13-16]. In the British zero-power reactors ZEUS and ZEPHYR the decay of the neutron flux as a function of time was measured [13] following insertion of control rods to a critical reactor in a rod-drop experiment. The measured neutron flux was fitted to a sum of exponents after correcting for residual multiplication. The group parameters were determined from the fitted parameters. These experiments, and similar ones [14], suffered from the large spatial distortion of the neutron flux due to the large negative reactivity insertion. In another experiment [15] smaller reactivity steps (-0.15$ to +0.30$) were applied to a critical reactor, resulting in a smaller spatial distortion. However, the delayed neutrons source could not be derived directly from these measurements. Instead, a least-squares fit was used to determine the delayed neutrons fractions using preset values of delayed neutrons constants. In a recently published work [16] noise measurements performed in a Brazilian reactor (IPEN/MB-01) operated in a critical state at very low power served to determine the delayed neutrons source in the frequency domain. The obtained results seem fair, though statistical fluctuations are quite large, and the experimental procedure is especially long and elaborated.

A new method for determining the delayed neutrons NER in the frequency domain, $g(\omega)$ (the Fourier components of $g(t)$), based on in-pile oscillation measurements was developed in this work. In these measurements the reactor itself serves as the measurement system. The reactivity oscillates around its critical state, power oscillations are measured, and kinetic equations are used in the derivation of NER in frequency domain analytically. In contrast to other in-pile measurements [13-15], this method does not require a multi-parameter fit process for determination of delayed neutrons NER.

Based on preliminary sets of measurements that have been performed in the IRR-I & IRR-II (Israeli Research Reactors I & II) [17] the method is demonstrated, and its potential to determine delayed neutrons NER accurately is discussed.

2. Experimental details

In the measurements discussed in this work trapezoidal reactivity oscillation, $\delta\rho_{ext}(t)$, was introduced to a critical reactor by periodically moving a regulating rod (IRR-II) or a piston containing a cadmium foil (IRR-I). Thermal neutron count rate oscillations, which are proportional to power oscillations, $\delta P(t)$, were measured using two ^{3}He detectors. In IRR-II the detectors were located in diffractometers KANDI II and

KANDI III, placed in two distinct radial tunnels. In IRR-I one detector was placed in a radial tunnel, and the other detector was placed in a tangential tunnel.

In IRR-II 72 measurements were carried out, with different oscillation periods in the range of 9.3 sec ÷ 500 sec (ω= 0.0126 rad/sec ÷ 0.68 rad/sec). In IRR-I 63 measurements were carried out, in the range of 9 sec ÷ 500 sec (ω= 0.0126 rad/sec ÷ 0.7 rad/sec). The shortest oscillation period in IRR-II (IRR-I) was limited by regulating rod (piston) mechanical constraints. Average reactor power was estimated to be 100 kW (1 kW), and the power oscillation was about 5% of the average power. The duration of each measurement was in the range of 0.5 hour ÷ 3 hours.

A computerized system controlled the reactivity oscillations and recorded the heights of the regulating rod (piston). This system also sent a synchronization signal to the neutron counting system at the beginning of each cycle. The measured neutron counts (typically around 30 kcps) were dead-time corrected ([18] based on [19]) using pre-measured values of ~3 µs. 25-100 ms time bins were used.

The IRR-II regulating rod height was translated to reactivity using a calculated calibration curve. In IRR-I, a linear dependence of reactivity with time was assumed between the "up" and "down" states of the piston.

Fuel, coolant, and moderator temperatures were continuously measured throughout all measurements, and negligible reactivity feedback was validated, as expected due to the low reactor power.

3. Theoretical Analysis

When reactivity feedbacks are negligible (e.g., when reactor power is very low), and reactivity oscillations are small compared to the average power - P_0 (so point-kinetics approximation [1] is valid), relative power oscillation is proportional to reactivity oscillation in the frequency domain [1]:

$$\frac{\delta P(\omega)}{P_0} = R(\omega)\cdot\delta\rho_{ext}(\omega), \tag{2}$$

where $\delta\rho_{ext}(\omega)$ and $\delta P(\omega)$ are the Fourier components of the reactivity and power oscillations, respectively, and $R(\omega)$, the "zero-power transfer function" [1], is a complex function. $R(\omega)$ can be expressed in terms of the delayed neutrons NER in the frequency domain - $g(\omega)$, delayed neutrons fraction and the generation time of the prompt neutrons - Λ:

$$R(\omega) = \frac{1}{i\omega\Lambda + \beta\left(1-g(\omega)\right)}. \tag{3}$$

In terms of the group parameters, the zero-power transfer function can be expressed in the following manner:

$$R(\omega) = \left(i\omega\Lambda + \sum_j \beta_j \frac{i\omega}{i\omega+\lambda_j}\right)^{-1}. \tag{4}$$

The highest angular frequency reached in these measurements was 0.7 $\sec^{-1}$. In this frequencies the prompt neutrons contribution to the zero-power transfer function is negligible. Therefore, $R(\omega)$ is governed by the delayed neutrons NER, which can be expressed by:

$$g(\omega) = 1 - \frac{1}{\beta} \cdot \frac{1}{R(\omega)} \quad . \tag{5}$$

Deriving $g(\omega)$ out of $R(\omega)$ using equation 5 requires knowledge of the value of β. β was not directly measured in the set of measurements described here. Therefore, it was estimated, utilizing the fact that $R(\omega)$ approaches β^{-1} asymptotically at high angular frequencies. Hence, we used $\frac{C}{R(\omega_{\max})}$ as an estimate for β, where $\omega_{\max}$ is the highest measured angular frequency and C is a calculated factor (based on the ENDF/B-VI group parameters) relating $R^{-1}(\omega_{\max})$ to β. Finally, the value of $g(\omega)$ in a specific angular frequency ω can be derived from the measured values of the zero-power transfer function, as follows:

$$g(\omega) = 1 - \frac{1}{C} \cdot \frac{R(\omega_{\max})}{R(\omega)} . \tag{6}$$

All the physical information given by the group parameters is contained in the values of $g(\omega)$ over the range [0.01 $\sec^{-1} \div 5 \sec^{-1}$]. Therefore, the group parameters can be derived by a least-squares fit on the measured values of $g(\omega)$. Alternatively, $g(t)$ can be obtained by performing inverse Fourier transform on the measured values of $g(\omega)$.

4. Experimental Results and Data Analysis

As an example of the data collected in each measurement, Fig. 1 presents the reactivity oscillation applied to IRR-II and the resulting power oscillation, measured by the two neutron detectors, in an 84 sec oscillation period measurement. Observing the power oscillations one can clearly notice the rapid change of power when the regulating rod is moving and the following delayed neutron contribution when the rod is at rest.

Fig. 2 presents the absolute values of the applied reactivity Fourier components and the power oscillation Fourier components in the above mentioned measurement. It is clear that the oscillation angular frequency (2π / 84 sec = 0.078 rad/sec) component of the power is two orders of magnitude higher than the neighboring components. This reflects the fact that reactivity noise in these measurements was negligible, as was certified in an independent background measurement. It is also interesting to notice the good agreement between the two detectors, which validates the point kinetics approximation used above. Since the reactivity signal is trapezoidal, odd harmonics of the oscillation frequency can also be observed with lower signal-to-noise ratio (even harmonics are absent because the reactivity signal is symmetric).

Equation 6 is used to derive $g(\omega)$ in each oscillation angular frequency ω. Since the reactivity noise was negligible, the statistical errors in these measured values resulted mainly from the normal distribution of the detector counts. These errors are inversely proportional to the square roots of the measurement duration and of the average detector counts. In our measurements these errors amounted up to 1.5% in the absolute value of the NER Fourier components.

Figure 1: Applied reactivity (top) and resulting power oscillation (bottom), as detected by KANDI III (black solid line) and KANDI II (blue dashed line), as a function of time, for an 84 sec period oscillation. For presentation purposes detector counts were averaged over 1 sec intervals.

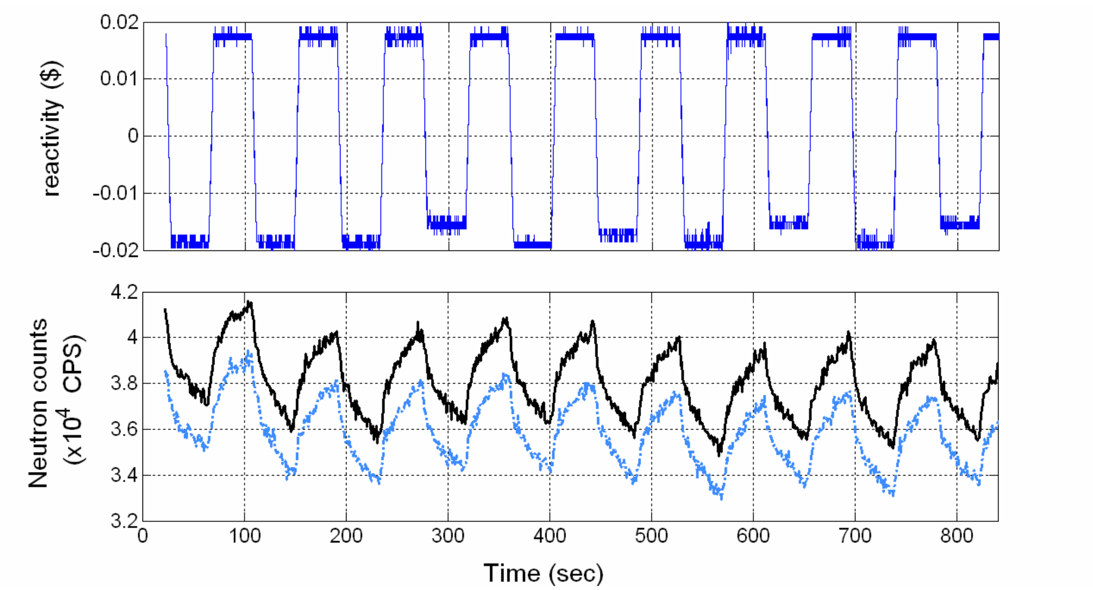


Figure 2: Absolute values of the applied reactivity Fourier components (top) and the power oscillation Fourier components (bottom), as measured by KANDI III (black ring) and KANDI II (grey circle) for an 84 sec period oscillation. The power oscillation Fourier components for each detector were normalized by its average count.

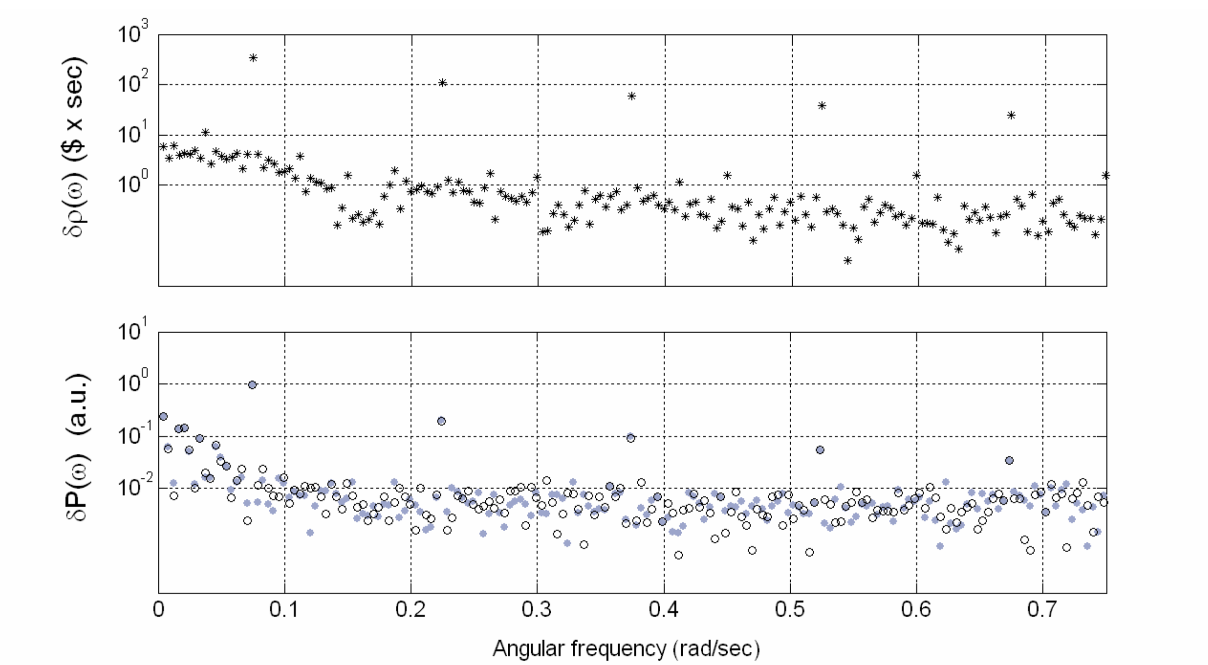


Fig. 3 and Fig. 4 summarize the results obtained using the above presented analysis. The absolute values of *g(ω)* measured in IRR-II (Fig. 3) and IRR-I (Fig. 4) are drawn as a function of angular frequency. The measured values are compared to calculated values based on Keepin [4], ENDF/B-VI [5], JEF-2.2 [6] and Brady & England [9] group parameters.

It is apparent from Fig. 4, and even more emphasized from Fig. 3, that the fluctuations in the measured values, as well as the differences between the values measured by the two detectors, are both much smaller than the discrepancies among literature values. Comparing the measured values with the calculated values based on various delayed neutrons group parameters sets, it is clear that the measured values in IRR-II, as well as in IRR-I, agree with the Keepin values significantly better than with the other sets. Taking into account that Keepin set is almost identical to the JENDL-3.3 [8] set, our results are further supported by the conclusions of Diniz and dos Santos [16].

Figure 3: Absolute values of *g(ω)*, as measured in IRR-II by KANDI II (blue) and KANDI III (black), as a function of angular frequency. Measured values are compared with calculated values based on Keepin (green), ENDF/B-VI (red), JEF-2.2 (magenta) and Brady & England (orange) group parameters. Calculated values account for photo-dissociation of deuterium [2] in heavy-water coolant and moderator of IRR-II.

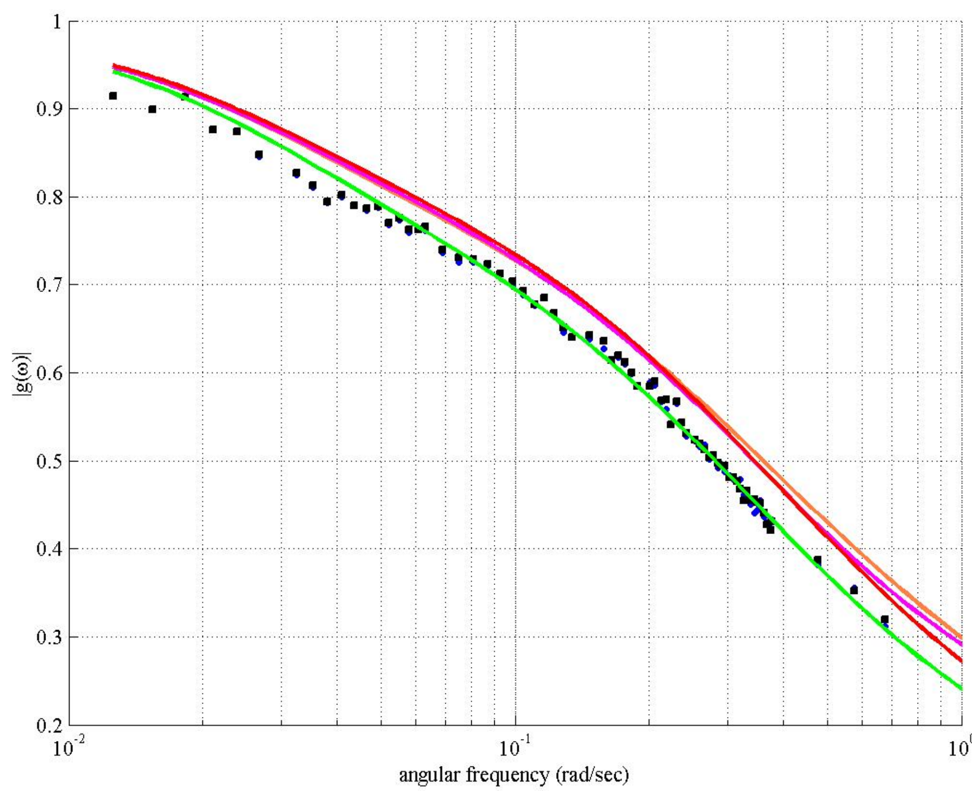
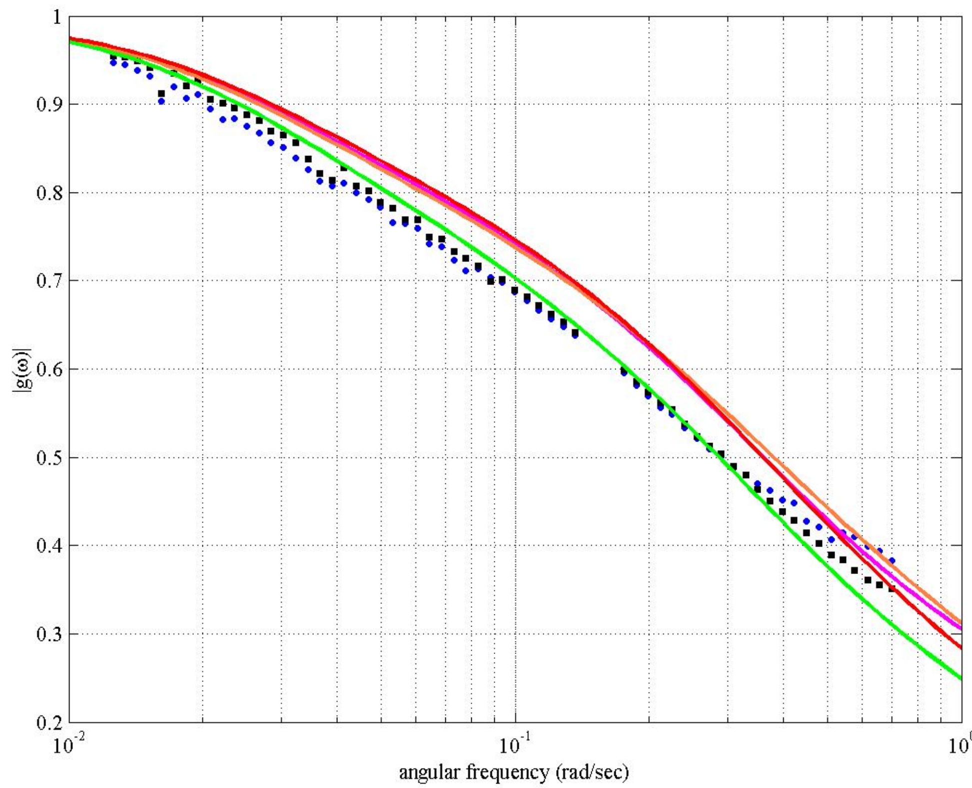


Figure 4: Absolute values of $g(\omega)$, as measured in IRR-I by the radial tunnel detector (blue) and tangential tunnel detector (black), as a function of angular frequency. Measured values are compared with calculated values based on Keepin (green), ENDF/B-VI (red), JEF-2.2 (magenta) and Brady & England (orange) group parameters.



In principle, the phases of $g(\omega)$ can also be derived from this type of measurements. Yet, the phases are much more sensitive to the exact experimental setup than the absolute values. In future work, we intend to analyze the errors in measured phases thoroughly, as well as extend the measured frequency range to higher frequencies. In this context, the relatively larger discrepancies between measured values in the two detectors in IRR-I at the high frequencies should be noted.

5. Conclusions

It is demonstrated that the method presented in this work is capable of providing with absolute values of delayed neutrons NER in the frequency domain with better accuracy (by a factor of 10) than discrepancies among NER results based on literature sets.

The measured values obtained in both reactors, IRR-I&II, agree very well with calculated values based on Keepin (and JENDL3.3, which are almost identical) group parameters in the measured frequencies range. This suggests a general conclusion, which is further supported by the results obtained by a different method at IPEN/MB-01 reactor [16]. The generality of the results obtained in this method will be further explored in future work, by investigating the similarity of delayed neutrons NER obtained in different reactors.

The final goal of these measurements is to determine accurately and independently a full set of delayed neutrons group parameters. This can be achieved by extending the measurements to higher angular frequencies (up to 5 sec^{-1}). This is essential in order to resolve the shortest-living delayed neutrons precursors.

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