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EXPERIMENTAL RESULTS FROM NOISE MEASUREMENTS IN A SOURCE DRIVEN SUBCRITICAL FAST REACTOR

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ABSTRACT

Both pulse counting techniques and continuous current measurements have been applied in the MASURCA subcritical fast reactor driven by the GENEPI pulsed neutron source in order to get the prompt neutron decay constant. The data from the pulse counting experiments were analysed using auto- and cross-correlation techniques, which are similar to one- and two-detector Rossi-α measurements, and Feynman-α techniques. The data from the continuous current measurements were analysed by calculating the Cross Power Spectral Density. We have found a good agreement between the values extracted from the auto- and cross-correlation techniques and from the cross-covariance and CPSD. The application of the time domain techniques becomes easier when there is no overlapping of the neutron chains originating from different source pulses. The application of the Feynman-α method shows some problems for pulsed systems, because of the dominance of the periodic terms in the variance-to-mean ratio, which leaves very little information to fit the prompt neutron decay constant. However, good agreement exists between our results and predictions from literature. Of the methods studied, CPSD is shown to be the best of the noise techniques to get the reactor decay time constant. It is applicable for a wide range of source frequencies and it converges rapidly comparing with subcritical systems driven by a radioactive source. In general, we conclude that the noise analysis techniques applied here are applicable to pulsed source driven systems.

Keywords: ADS, MUSE, fast reactor, pulsed source, noise techniques.

1. INTRODUCTION

The safe operation of Accelerator Driven Systems (ADS) requires the development of methods to monitor the subcriticality of the reactor, (Gandini and Salvatores, 2002). Within the Fifth European Framework Programme, the MUSE project has as an objetive the investigation of the applicability of zero-power noise methods to measure kinetics parameters like the prompt neutron decay constant of a subcritical reactor driven by an accelerator. To this end, the GENEPI deuterium accelerator developed by CNRS (Billebaud et al, 2002) has been coupled to the MASURCA fast reactor at CEA loaded with MOX fuel (Soule, 2002). The accelerator can operate using either a deuterium target or a tritium target. For all measurements in this paper, the deuterium target has been used, delivering neutrons with energy of about 2.45 MeV at a source intensity of about 4×10^4 neutrons per pulse each with width of less than 1 μs, and at a maximum repetition rate of 4.5 kHz.

Classical noise analysis method like Rossi-α, Feynman-α and transfer function analysis (Serber, 1945, Feynman et al (1965), Uhrig, 1970, Williams, 1974) have been applied to the MASURCA reactor at critical configuration and preliminary results have been published by Billebaud et al (2002), Kloosterman et al (2002), Rugama et al (2002) and James et al (2002). In this paper, the same techniques have been applied to the reactor at subcritical state (reactivity of about –455 pcm, pcm=10^{-5} $\Delta K_{eff}/K_{eff}$) driven by the GENEPI pulsed neutron source described above. To include the dynamic aspects introduced by the time dependency of the source, the theoretical expressions for the classical methods had to be modified. To this end, Pazsit and Ceder (2002) and Yamane et al (2002) derived new formulas for the Feynman-α analysis, while Rugama et al (2003) derived formulas for the transfer function analyses.

In this work we describe the experimental set-up and measurement systems used by the Interfaculty Reactor Institute (IRI) of Delft University of Technology, some theoretical aspects of Rossi-α, Feynman-α and transfer function measurements in a pulsed subcritical fast reactor, and a first comparison of measurements and theoretical predictions. Furthermore, a simple formula for the Rossi-α using point kinetics has been derived together with a simplified expression for the transfer function.

2. EXPERIMENTAL CONFIGURATION

Two Data Acquisition Systems (DAQs) have been developed by IRI to record data both in pulse mode and in continuous current mode. The pulse counting technique requires a fine time resolution, because MASURCA is a fast reactor and because of the source pulsed at a high repetition rate. The measured neutron pulses from the fission chambers are discriminated from the gamma pulses and shaped into a square TTL pulse of 50 ns with amplitude of 5 to 8 V. The resolution of the measurement system is also 50 ns, which in practice means that the neutron detections are measured with an accuracy of ±25 ns.

The measurements in continuous current mode have been performed with a pair of high efficiency fission chambers placed close to detectors A and C (see Fig. 1). Each fission chamber contains about 4.5 gram of U-235. A high bandwidth current to voltage converter and amplifier is used to record the fission chamber current. The amplifier includes a high-pass filter to remove the high voltage DC part in the signal. After additional amplifiers and anti-alias filters the signal is sampled and recorded by PC. The acquisition was performed at a sampling frequency of 40 kHz and the analysis was done using 2048 time bins. This current measurement technique (for low frequency bandwidth) is well known from the practice of monitoring power reactors (Thie, 1981). Because the neutron detections in the fission chamber lead to a saturated current, no dead time correction is needed. The disadvantage of this method is that no discrimination between neutron and gamma detections can be made.

Two facilities have been coupled at CEA (Cadarache) for the MUSE-4 project. The MASURCA fast reactor is loaded with MOX fuel and sodium pins to simulate the sodium coolant (Soule, 2002). Furthermore, the core contains a vacuum tube for the deuterium beam, at the end of which a deuterium or tritium target is positioned. A lead buffer zone surrounds the target to simulate the influence of a spallation target on the neutron spectrum that would be present in ADS driven by a high-energy proton beam. A stainless steel-sodium reflector surrounds the core. Axially the core is shielded with stainless steel and in the radial direction with iron. GENEPI is a deuteron accelerator producing neutrons at the core centre from either the $D(d,n)^3He$ or the $T(d,n)^4He$ reaction (Billebaud et al, 2002). It can operate with a repetition rate between 50 Hz and 4.5 kHz.

Fig. 1 shows the horizontal cross section at core mid plane with some of the detector positions. For the present work, only U-235 fission chambers (1gr ^{235}U) located in the reflector region (A, B, C and D) and two (very sensitive, 4.5gr ^{235}U) fission chambers located at those positions for current mode measurements were used.

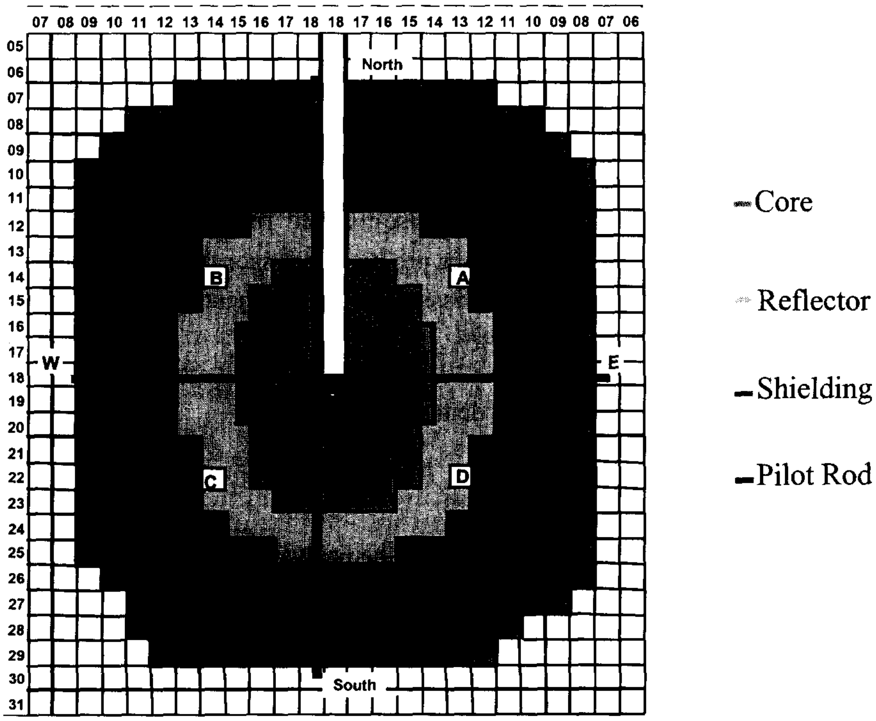

Fig. 1: Horizontal cross section of the MASURCA core at midplane, with the detector positions indicated.

Measurements were performed at two different subcritical states in the SC0 configuration, depending on whether or not the pilot rod was inserted. The Pilot Rod is a fuel assembly covered partially by aluminium and partially by polyethylene. The pilot rod inserted means that the polyethylene area is the fuel region. The worth of the pilot rod during the measurements was about -124 pcm, and the reactivity value given by CEA at SC0 configuration with the pilot rod inserted was about –455 pcm. The effective delayed neutron fraction β and the neutron generation time Λ used in the analyses were calculated from a measurement at critical ($\beta/\Lambda = 5840 \pm 200\ \mathrm{s}^{-1}$)

3 TWO DETECTOR ROSSI-ALPHA THEORY AND MEASUREMENTS

Two different neutron sources are present in the coupled system: the inherent source due to the higher actinides with strength of about $1.3\times10^{8}\,\mathrm{ns}^{-1}$ (Rugama et al, 2002) and the neutrons coming from the external source (deuterium target). The magnitude of both sources is similar from the statistic point of view but differ for the dynamics.

The Rossi-α method involves time correlation of detection events in one detector or between different detectors. Correlation comes from neutron-induced fissions and from spontaneous fission. The two-detector cross correlation is defined as the joint probability of one neutron detection at time t_2 in dt_2 and another detection at time t_1 in dt_1 following a spontaneous fission event of the inherent source or a pulse event from the pulsed source at time t_0 in dt_0. The expression of this joint probability has been derived using point kinetics:

$$P(t_2,t_1,t_0) = \frac{\varepsilon_1\varepsilon_2\left[\frac{F_I\bar{\nu}_I + F_P(t_0)}{\alpha\Lambda}\overline{\nu(\nu-1)} + F_I\overline{\nu_I(\nu_I-1)}\right]}{(\bar{\nu}\Lambda)^2}\exp(-\alpha(t_2+t_1-2t_0))dt_2dt_1dt_0 \tag{1}$$

Where F_I is the inherent fission rate and $F_P(t)$ the pulse-induced fission rate with time dependence coming from the pulsed source. The number of neutrons produced per spontaneous fission is ν_I while the number of neutrons produced per neutron-induced fission is ν. The neutron generation time and the detector efficiency are given by Λ and ε_i, respectively.

Assuming that the pulse can be expressed as a Dirac delta function:

$$S(t) = S_0\delta(t) \tag{2}$$

and considering only one source pulse per time window in the analysis, the probability of a chain related count at time t_2 in dt_2 and at time t_1 in dt_1, is the integral of the equation (1) over time t_0 from $-\infty$ up to the first detection event at t_1. The probability can be expressed as a function of the time difference between the detections $\tau = t_2 - t_1$.

$$P(\tau)d\tau = \frac{\varepsilon_1\varepsilon_2\left[\frac{F_I\bar{\nu}_I + F_P}{\alpha\Lambda}\overline{\nu(\nu-1)} + F_I\overline{\nu_I(\nu_I-1)}\right]}{(\bar{\nu}\Lambda)^2}\frac{\exp(-\alpha|\tau|)}{2\alpha}d\tau \tag{3}$$

The expression (3) is the correlated term of the cross correlation between two detectors, and corresponds to the covariance function. To get the expression for the correlation function we should add the term due to the accidental coincidence counts, which is the product of the count rates of the two detectors times the interval over which the counts are acquired.

Pulse mode measurements have been performed with detectors B and D in the reflector with GENEPI operating at a repetition rate of 1 kHz. In Fig. 2, the covariance function is presented together with the fit curve that gives an alpha value of 15523±142 rad.s^{-1}, which is in good agreement with the value expected for the SC0 configuration with the pilot rod not inserted. This technique has also been applied to the configuration with the pilot rod inserted, which gave an alpha value of 13348±141 rad.s^{-1}. The nonlinear regression method used to fit the curves is based in the Levenberg-Marquardt algorithm.

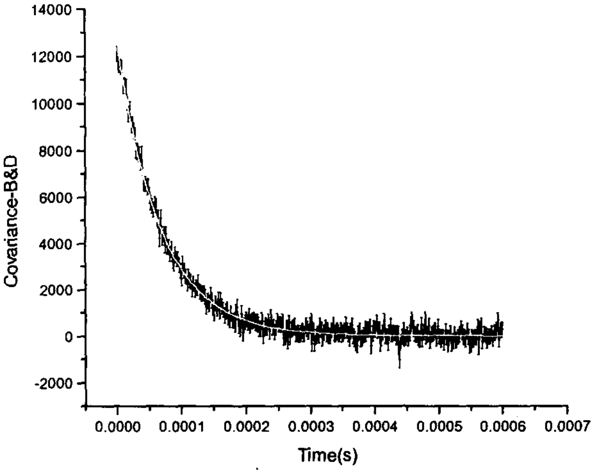

Fig. 2: Cross-covariance curve of the measurements with fission chambers B and D in the reflector for the SC0 configuration with the pilot rod not inserted and with GENEPI operating at a repetition rate of 1 kHz.

In table 1 we compare the alpha values and reactivities from the application of the cross-correlation method at both configurations, Pilot Rod in and out.

Pilot Rod	**Alpha (rad/sec)**	**Reactivity (pcm)**
inserted	13348	426
Not inserted	15523	550

Table 1 comparison alpha value and reactivity at two configurations

As was done for equation (3) we have derived the expression of the auto-correlation function using point kinetics. The auto-covariance function is written as:

$$C_{D_1D_1}(\tau)=\frac{\varepsilon_1{}^2\left[\dfrac{F_I\bar{\nu}_I+F_P}{\alpha\Lambda}\overline{\nu(\nu-1)}+F_I\overline{\nu_I(\nu_I-1)}\right]}{(\bar{\nu}\Lambda)^2}\frac{\exp(-\alpha|\tau|)}{2\alpha}+\varepsilon_1\left[\frac{F_I\bar{\nu}_I+F_P}{\alpha\Lambda}\right]\delta(\tau) \qquad (4)$$

Equations (3) and (4) differ only in the second term of equation (4), which is the white noise component (Uhrig, 1970, Williams, 1974). From the same measurement data used in Fig. 2 (the SC0 configuration with the pilot rod not inserted), we have plotted the auto-covariance curves for both detectors B and D (see Fig. 3). The first time bin has been removed to eliminate the white noise component in this function. The fitted alpha values are 15580±132 rad.s^{-1} for detector B and 15556±140 rad.s^{-1} for detector D.

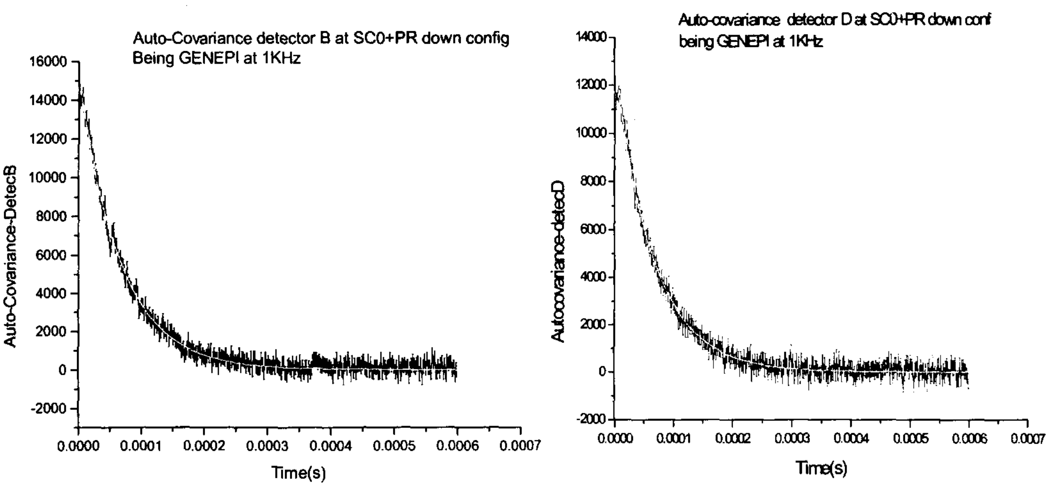

Fig. 3: Auto-covariance curves of the measurements with fission chambers B and D in the reflector for the SC0 configuration with the pilot rod not inserted and with GENEPI operating at a repetition rate of 1 kHz .

The measurement time for the analysis of the auto- and cross-covariance curves was 35 minutes. Compared with the measurements performed at the same configuration but without the external source (Rugama et al, 2002), this technique converges much faster for a system driven by an external pulsed source. This is due to the fact that each source pulse triggers a large number of fissions leading to highly correlated neutrons being detected in both fission chambers. These first results demonstrate the applicability of the two-detector Rossi-α method in future ADS working at zero power and driven by a pulsed source.

As shown in equation (1) the external source fission rate depends on the frequency of the pulsed source. If the accelerator frequency becomes higher than the reactor break-frequency the prompt neutron chains will start to overlap. Fig. 4 presents the correlation for a source frequency of 4.4 kHz and for reactivity equal to that in Fig. 2. Clearly, an overlapping of chains can be seen in the correlation, which implies that the alpha value cannot be obtained as easily as was done in Fig. 2.

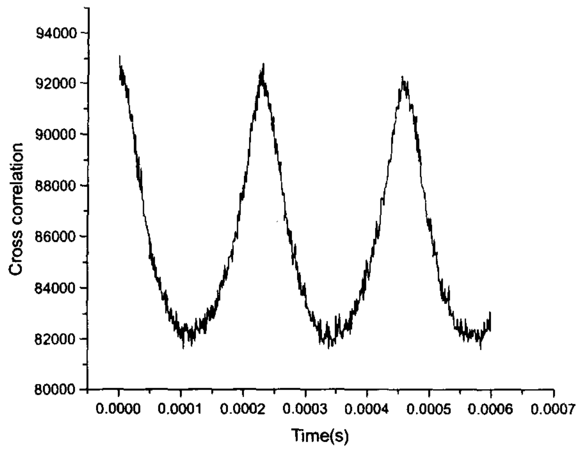

Fig. 4: Cross-correlation of the measurements with fission chambers B and D in the reflector for the SC0 configuration with the pilot rod inserted and with GENEPI operating at a repetition rate of 4.4 kHz.

We conclude that direct application of this technique is limited to source frequencies lower than the characteristic reactor break frequency, and that a more sophisticated formulation is needed to make this technique suitable for a wider range of frequencies.

4 FEYNMAN-ALPHA MEASUREMENTS WITH A PULSED SOURCE

For a Poisson distribution, the variance of the number of counts in a fixed time interval equals the mean value of the counts. In case of multiple-neutron emission events that initiate the prompt neutron chains, the variance is larger than the mean, and one can extract the prompt neutron decay constant from the variance-to-mean ratio using the well-known Feynman-α formulation (Uhrig, 1970, Williams, 1974).

Not surprisingly, for a pulsed reactor system, the well-known Feynman-α formulation has to be adapted to include the time-dependence of the source. As shown by Pazsit and Kuang (2001), the variance-to-mean ratio depends on the accelerator frequency. In this paper we have used the Feynman-α expression developed by Pazsit and Ceder (2002) for a stochastically pulsed system, which in practice means that in the analysis of the experimental data, the start of each time interval is chosen randomly with respect to the source pulses. Because of the temporal correlation between source neutrons, the variance-to-mean ratio as a function of the width of the time interval shows ripples that can be described by periodic functions as follows (Pazsit and Ceder, 2002):

$$Y(\tau)=\frac{\sigma^2(\tau)}{\mu(\tau)}-1=\frac{2\varepsilon S_0 T_p^5\alpha}{\tau\pi^4}\sum_{n=0}^{\infty}\frac{1}{4n^6\pi^2+n^4\alpha^2T_p^2}\sin^2(\frac{\pi n\tau}{T_p})+\frac{\varepsilon\lambda_f\overline{(\nu(\nu-1)}}{\alpha^2}(1-\frac{1-e^{-\alpha\tau}}{\alpha\tau}) \quad (5)$$

Where σ^2 is the variance, μ the mean value and T_p the period of the pulsed source.

Measurements were performed at the same condition as for the two-detector Rossi-α experiments (SC0 configuration with the pilot rod not inserted, see Section 3) with an accelerator repetition rate of 4.4 kHz. In Fig. 5, the curve of the variance-to-mean minus one is plotted for detector B as a function of the width of the time interval. In principle, the alpha value could be extracted from this curve using equation (5). However, in equation (5), the last term corresponds to the variance-to-mean ratio with a continuous source. The source period T_p is about two times shorter than the inverse of the time decay constant ($1/\alpha$). This means that in Fig. 5 only two minima contain information on the alpha value, which is not sufficient to extract from these data an accurate value for alpha. More measurements are planned, but our preliminary thought is that the Feynman-α technique for stochastically pulsed sources cannot be used for MUSE because SC0 is the least subcritical of all configurations planned in the project.

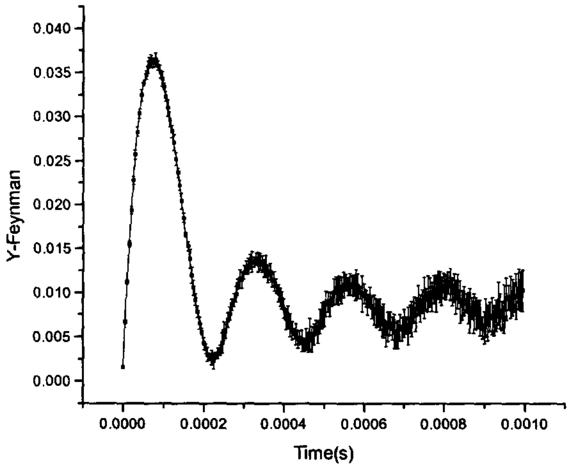

Fig. 5: The variance-to-mean ratio minus one $\left(Y=(\sigma^2/\mu)-1\right)$ as a function of the gate width for a stochastically pulsed system in the SC0 configuration with the pilot rod not inserted, and with GENEPI operating at a repetition rate of 4.4 KHz.

A second type of analysis proposed by Pazsit and Ceder (2002) and Yamane et al (2002) is a Feynman-α technique using deterministic pulsing. In this case, the gates used in the analysis are synchronised with the accelerator pulses. As shown in Fig. 6, this second type of analysis has the advantage that the oscillating deviations from the smooth Feynman-α curve are much smaller. The trends predicted by Pazsit and Ceder (2002) and Yamane et al (2002) are confirmed quite well by these experimental data, but the extraction of the correct alpha value is still quite difficult.

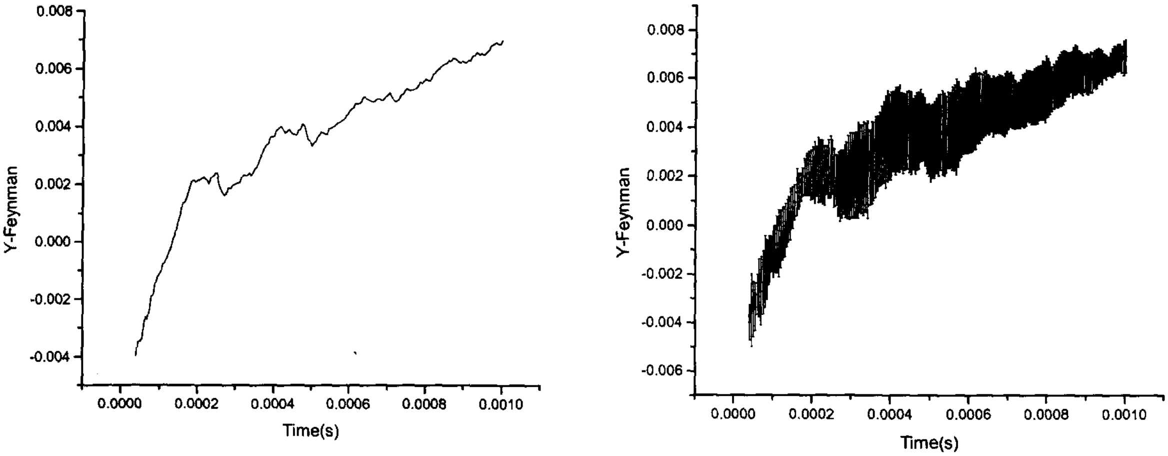

Fig. 6: The variance-to-mean ratio minus one $\left(Y=(\sigma^2/\mu)-1\right)$ as a function of the gate width for deterministically pulsed system in the SC0 configuration with the pilot rod not inserted, and with GENEPI operating at a repetition rate of 4.4 KHz with and without error bars.

5. CROSS POWER SPECTRAL DENSITY THEORY AND MEASUREMENTS

The last technique that we studied in this work is transfer function analysis using the Cross Power Spectral Density. The measurements were performed in continuous current mode using the hardware and software described in Section 2. A theoretical expression that includes the time dependency of the source has been developed by Rugama et al (2003) using stochastic transport theory. In this paper we use a simpler expression based on point kinetics, which is justified by the fact that MASURCA is a small core and that the reactivity is not very low. However, future applications may need an expression based on spatial kinetics.

Considering that the CPSD is the Fourier transform of the covariance, the transfer function of our system is the Fourier transform of equation (3) with more than one pulse per time window present in the analysis.

To simplify the mathematical derivation of this expression, we assume that the time dependency of the source can be described by a train of Dirac delta pulses, as has been done for the other techniques like the Rossi-α and Feynman-α:

$$S(t) = S_0 \sum_{n=0}^{N} \delta(t - nT_p) \tag{6}$$

Assuming that the number of pulses per time window in the analysis is N, after some manipulation the CPSD is:

$$CPSD_{D_1D_2}(w) = \frac{\varepsilon_1\varepsilon_2}{2\alpha(\bar{\nu}\Lambda)^2}\left[\frac{F_I\bar{\nu}_I + F_S\sum_{n=0}^{N}\exp(-iwnT_p)}{\alpha\Lambda}\overline{\nu(\nu-1)} + F_I\overline{\nu_I(\nu_I-1)}\right]\frac{1}{(\alpha^2+w^2)} \tag{7}$$

From this expression we can conclude that the CPSD₂₃ depends on the source frequency ($\Theta = 2\pi/T_p$) and the reactor break frequency α. Both the inherent source and the pulsed source have been included in the derivation of equation (7). It is seen that the CPSD shows peaks corresponding to the source frequency and its harmonics.

Measurements were performed in subcritical configuration with the pilot rod inserted. In Fig. 7, the CPSD is plotted together with the fit.

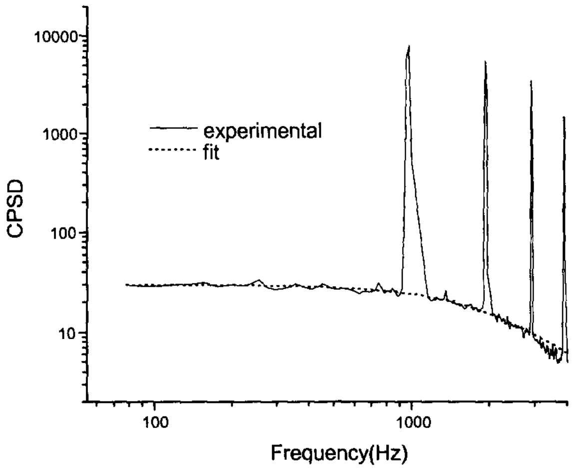

Fig. 7: The CPSD of the measurements with fission chambers C and D in the reflector for the SC0 configuration with the pilot rod inserted and with GENEPI operating at a repetition rate of 1 kHz.

To avoid the peaks in the fitting, we have used a weight function proportional to the inverse of the variance function at each point, except in the peaks, where the weight function was taken zero (infinite variance). The prompt neutron decay constant we obtained from this fitting procedure was 13251±265 rad/s. The second method we propose consists of removing the peaks before fitting, the alpha value from that fitting was 13258±273 rad/s. Both fits are in good agreement. It was verified that the transfer function related to the signal transmission and amplification/filtering steps between the detector and the PC has a negligible influence in the frequency bandwidth used in both fits (70Hz, 3.5kHz).

Contrary to the cross-correlation method described in Section 3, this continuous current technique is more favourable for measurements at higher source frequencies. The measurement set-up, however, will limit current mode measurements. The frequency bandwidth that can be measured is limited by the capacitance of the cable between fission chamber and current amplifier and/or by the amplifier characteristics itself. Another limitation in MASURCA might be the very small magnitude of the signals coming from the detectors when the multiplying assembly is very subcritical.

CONCLUSIONS

Two different measurement techniques have been applied to the MASURCA fast reactor driven by the GENEPI pulsed neutron source: pulse counting measurements and continuous current measurements. Three reactor noise analysis methods were studied in the new configuration: auto- and cross correlation measurements, Feynman-α techniques and analysis of the Cross Power Spectral Density (CPSD) in the frequency domain.

We have found a good agreement between the values of the prompt neutron decay constant extracted from the auto and cross-correlation techniques (between 15523 to 15580 rad.s^{-1} for the SC0 configuration with the pilot rod not inserted), and from the cross-covariance and CPSD (between 13251 and 13348 rad.s^{-1} for the SC0 configuration with the pilot rod inserted). The application of the correlation techniques corresponds to the instantaneous source when there is no overlapping of the neutron chains originating from different source pulses. As for the Pulse Neutron Source method, the source frequency is the main limitation for the application of the correlation technique. The results presented here demonstrate that the noise analysis techniques, used in subcritical systems driven by a pulsed source, are capable of accurately characterising the reactor time decay constant of a multiplying system.

The application of the Feynman-α method exhibits difficulties when applied to stochastically and deterministically pulsed systems. The dominance of the periodic terms in the variance-to-mean ratio, leaves very little information to fit the prompt neutron decay constant α. However, the experimental results seem to confirm the theoretical expressions derived in literature.

The analysis of the CPSD is the best of the methods studied. It is applicable for a wide range of source frequencies and it converges fast compared with the systems driven by radioactive or constant sources. Although in current mode measurements we need the use of high-efficiency fission chambers. Once the peaks due to the pulsing of the source are removed from the results, the analytical expression for the prompt neutron decay constant can be by the well-know transfer function for a subcritical system driven by a stationary source. As mentioned before, the prompt neutron decay constant obtained by using time and frequency domain techniques are in reasonable good agreement (13348 and 13251 rad.s^{-1}, respectively, for the SC0 configuration with the pilot rod inserted).

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