Flash Algorithms for Power Noise Analysis at The IBR-2M Nuclear Reactor

Mihai Dima[1*], Yuri Pepelyshev[2], Tayibov Lachin[3]

[1] Institute for Physics and Nuclear Engineering, DFCTI, R-76900 Magurele, Bucharest, Romania

[2,3] Joint Institute for Nuclear Research, FLNP, RU-141980 Dubna, Moscow, Russia

[*]modima@nipne.ro

***Abstract* - Neutron noise spectra in nuclear reactors are a convolution of multiple induced reactivities. For the IBR-2M pulsed nuclear reactor (JINR-Dubna) part is represented by the reactivities induced by the two moving auxiliary reflectors and part by other sources that are moderately stable. In the present study, we present real-time algorithms for detecting power noise baseline and its advantages in the subsequent Fourier (DFFT) processing.**

Keywords - Neutron Noise; Nuclear Power; Flash Algorithms

I. INTRODUCTION

Neutronic processes in nuclear reactors have a probabilistic character due to the quantum mechanics of scattering and the stochastics of propagation in materials. Design is mostly performed using the equations of neutron flux transport (in energy and space) and associated effects (fission, thermal fluxes, etc). The statistical deviations from average quantities give however the complete image of neutron physics in the reactor - the so termed Neutron Noise, described using Markov-chain theories. The theories associated with the underlying stochasticity that produces these fluctuations are actually century-old [1], stemming from population studies. It was shown that (Alphonse) de Candolle's conjecture on the extinction of family names [2] leads, if applied to neutron chains, to non-ergodic behavior. Such theories were picked up in nuclear physics by Feynman, de Hoffmann and others to describe neutron processes in fission [3], leading to the Feynman α-formula:

$$\frac{\sigma_Z^2(t)}{\langle Z(t)\rangle} = 1 + \epsilon\Big(1 - \frac{1-e^{-\alpha t}}{\alpha t}\Big) \quad (1)$$

which shows the fluctuations (i) being over-poissonian - due to correlations of neutrons in the same chain and (ii) the neutrons produced in the same group statistically disappearing (exponentially) all at the same time. The modern theoretical approach is given by the Pal-Bell equation [4], as an applied case of the Chapman-Kolmogorov master equation to Markov-chain neutron processes.

On top of the neutron stochastic behavior is the modulation of the neutron flux by various reactivities: some due to 2-phase liquid flow (bubbling), fuel embrittlement, or mechanically induced reactivities, etc. Any addition to the spectrum can be thus detected and classified, issuing a specific warning. In this respect neutron noise spectrum analysis is a very far reaching tool in nuclear safety.

II. THE IBR-2M REACTOR

The IBR-2M [5] is a modification of the IBR-2 (2 MW nominal power) pulsed research fast-reactor with PuO_2 fuel elements. The reactor coolant is liquid sodium. The pulsed mode operation is enabled by a reactivity modulator consisting of two rotating parts: the main movable reflector (OPO, at 1500 rpm) and the auxiliary movable reflector (DPO, at 300 rpm) as shown in Figure 1. Each reflector creates reactivity pulses. For nominal DPO rotation speed the reactivity of every fifth pulse is positive - i.e. the reactor becomes prompt neutron-supercritical for ca. 0.400 ms (0.215 ms half-width), with a repetition frequency of 5 Hz (Figure 2). As a result, powerful power pulses of 5Hz repetition frequency take place in the reactor.

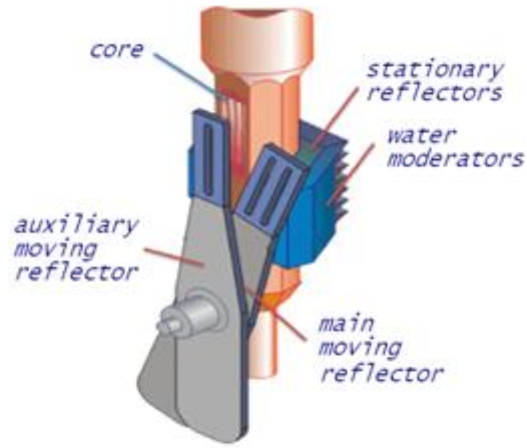

Figure 1: Details of the IBR-2M reactor showing the active core and two movable reflectors.

The pulsed operation mode of the reactor is established when the prompt neutron supercriticality (δk - β) reaches the ``equilibrium'' value $\varepsilon_m = \varepsilon_{m0} \sim 1 \cdot 10^{-3}$ (at 5 Hz) at which the reactor can be periodically pulsed. For supercriticality smaller than the ``equilibrium'' value, the amplitude (and consequently the energy) of each subsequent pulse is smaller than that of the previous one, which means that the reactor is attenuating. There are two main causes for pulse energy fluctuation in the reactor: the stochastic character of fission and neutron multiplication processes, and the fluctuation of external reactivity. Stochastic noise dominates power fluctuations at low neutron intensity, for powers below 1W. Pulse energy fluctuations at high power have adverse effects on the operation of the reactor: in the dynamics, startup and adjustment process, performance of the experimental equipment, etc. However power fluctuations also have a positive aspect, that as a tool for reactor diagnosis. The most important characteristic of a pulsed reactor is the relative dispersion of pulse energy fluctuations:

$$(\sigma_Q/\bar{Q})^2 = \Delta_{st}^2(1+\delta_0^2)+\delta_0^2 \tag{2}$$

where $\Delta_{st}^2 = \nu\Gamma/2S\tau$ is the relative dispersion of stochastic fluctuations; δ_0^2 the relative dispersion of noise caused by external reactivity fluctuations; Γ and ν the dispersion of the number of prompt neutrons, respectively the average number of neutrons in a single fission event respectively; τ the lifetime of prompt neutrons in the core; $S = S_{sp} + S_{del}$ the neutron source intensity (that operates continuously during the pulse); S_{sp} the intensity of spontaneous neutrons and those from the (α, n) reaction on oxygen ^{18}O (part of the oxide fuel); $S_{del} = \beta_{eff}\nu F$ and β_{eff} the intensity, respectively effective fraction of delayed neutrons; $F = L\cdot W$ the fission rate; L the number of fission events in a second per watt; W the absolute reactor power. At high power (for IBR-2M above 100 W) the fluctuations of the external reactivity (component δ_0^2) dominates. All noise diagnostics of the reactor are based on research of this noise component.

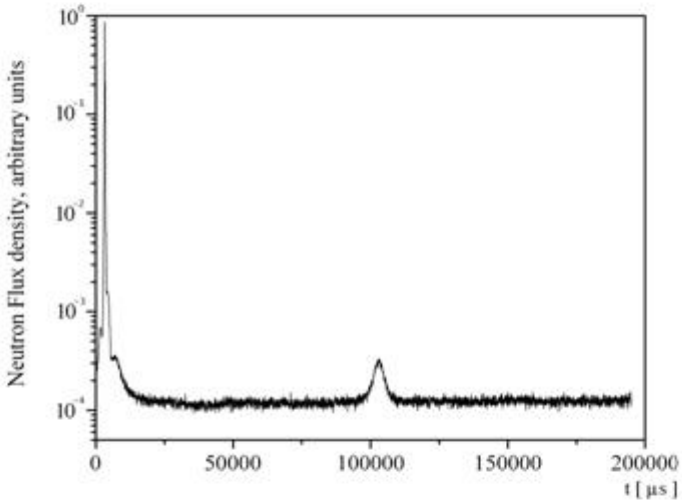

Figure 2: Power versus time, between two subsequent pulses. Data is normalised to the pulse maximum.

III. POWER NOISE BASELINE

For a power-noise analysis [6], we must first extract any reactor-dynamics influences from the recorded waveforms (overcompensation by the Automatic Regulation power control rod, etc). In this respect we want to determine a baseline with respect to which to reference the instantaneous power and, by subtraction, to obtain the power noise. Such method is evidently of general use in all power-generating systems, where noise is generated by transformer core non-linearities, switch activities, reactive loads, etc. It is also of like interest to large digital/analogue circuits, which need to pacify analog ground, or digital circuits with low noise margins [8].

We assume that around any given time-point, in a range of $x \in [-z, +z]$ time bins, we can Taylor-expand the baseline, function of time, as a polynomial of order k. To find the coefficients we apply a least square fit:

$$\left\langle \left(\sum_{j=0}^{k} a_j x^j - y \right)^2 \right\rangle = \text{minimum} \tag{3}$$

where the average sign <…> is taken over all time bins in the range [-z, +z].

This implies that:

$$\sum_{j=0}^{k} \langle x^{i+j} \rangle a_j = \langle yx^i \rangle \tag{4}$$

respectively $a_0 = \Delta_0 / \Delta$ where:

$$\Delta_0 = \begin{vmatrix} \langle x^{2k}\rangle & \langle x^{2k-1}\rangle & \ldots & \langle x^{k-1}\rangle & \langle yx^{k}\rangle \\ \langle x^{2k-1}\rangle & \langle x^{2k-2}\rangle & \ldots & \langle x^{k-2}\rangle & \langle yx^{k-1}\rangle \\ . & . & \ldots & . & . \\ . & . & \ldots & . & . \\ . & . & \ldots & . & . \\ \langle x^{k+1}\rangle & \langle x^{k}\rangle & \ldots & \langle x^{2}\rangle & \langle yx^{1}\rangle \\ \langle x^{k}\rangle & \langle x^{k-1}\rangle & \ldots & \langle x^{1}\rangle & \langle yx^{0}\rangle \end{vmatrix}$$

$$\Delta = \begin{vmatrix} \langle x^{2k}\rangle & \langle x^{2k-1}\rangle & \ldots & \langle x^{k-1}\rangle & \langle x^{k}\rangle \\ \langle x^{2k-1}\rangle & \langle x^{2k-2}\rangle & \ldots & \langle x^{k-2}\rangle & \langle x^{k-1}\rangle \\ . & . & \ldots & . & . \\ . & . & \ldots & . & . \\ . & . & \ldots & . & . \\ \langle x^{k+1}\rangle & \langle x^{k}\rangle & \ldots & \langle x^{2}\rangle & \langle x^{1}\rangle \\ \langle x^{k}\rangle & \langle x^{k-1}\rangle & \ldots & \langle x^{1}\rangle & \langle x^{0}\rangle \end{vmatrix} \tag{5}$$

The sampling structure of the data-acquisition (DAQ) chain is known in advance, meaning Δ is known at run-time. Likeso are the minors of Δ_0, hence $a_0 = \mathrm{LIN}\{ \langle yx_j\rangle \}$ with known coefficients.

The last obstacle is evaluating $S_j = \langle yx^j\rangle$ at run-time in an expeditive manner. Take for instance $S_0 = \langle yx^0\rangle$, the procedure is straight forward: in moving to the next time point we subtract the low endpoint and add the new high endpoint, thereby updating S_0. The situation becomes more complex for S_j, where the powers of x^j are involved. In principle these are known and can be tabled, then multiplied. Still, if the interval [-z, +z] is large this can be quite CPU intensive.

More often the order k is low and (possibly) z large. It would make sense then to store S_j^{old} and use them in calculating S_j^{new}. We exploit the fact that in updating S_j we move from x^j at any given point, to $(x-1)^j$. The latter can be expanded as a binomial series:

$$(x-1)^j = \sum_{i=0}^{j} C_j^i x^{j-i}(-1)^i \tag{6}$$

rendering useful the previously computed S_j's:

$$S_k^{\text{new}} = y_{z+1}z^k + (-1)^{k+1}y_{-z}(z+1)^k + \sum_{i=0}^{k-1} C_k^i (-1)^{k-i} S_i^{\text{old}} \tag{7}$$

This is a much faster computation than any other method, allowing to draw a_0 (the baseline) in real-time for a number of quite complex functions (in *long double* precision up to order k = 40/ln(z)).

Figure 3 shows the IBR-2M reactor startup power (red line) with a detail insert. The baseline was determined with a k = 3 order polynomial, over a time interval [-30, +30] around current time point. This takes away from the Fourier spectrum some of the low-frequency features belonging to reactor dynamics.

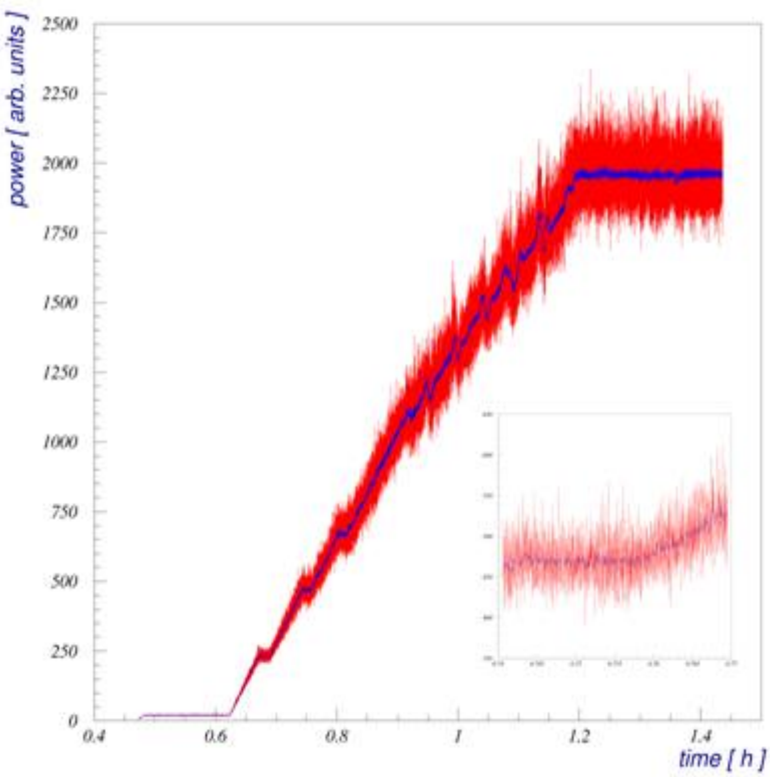

Figure 3: Reactor power during power up (red line) with fitted baseline (blue curve, of order k = 3, over a time interval [-30, +30] bins). This takes away from the Fourier spectrum some of the low-frequency features belonging to reactor dynamics.

IV. POWER NOISE FOURIER SPECTRUM

As mentioned in the introduction there are beneficial aspects to the DFFT Fourier transform [7] in having detected and subtracting the baseline. Apart from extracting from the low frequency end reactor-dynamics features, also technical aspects are achieved, such as rejecting aliasing. In general such unwanted phenomenon is due to some frequency much higher than the Nyquist sampling frequency - in our case $f_{Ny} = 1/2\Delta t = 2.5$ Hz. Imagine the effect of 50 Hz ripple for instance, or that of certain reactor chirps. Active analog filters would come to mind as first resource since they have a somewhat higher Q-factor than passive filters. (Passive filters in the range [0, 2.5 Hz] are too bulky in our view of a DAQ setup.) Still, even active filters do not have that high Q-factors - and if they do, 50 Hz sources do have a certain bandwidth, rendering useless very high-Q filters. As for reactor chirps they are broad bandwidth and impossible to filter. All these phenomena create unwanted aliasing that is impossible to remove in any traditional way. Fortunately, the effect is present for both raw data and for the baseline fit. Subtracting one from another yields a clean noise signal reliable for physics studies of the reactor. Figure 4 shows the Fourier transform of the reactor power, baseline and noise. It can be seen that the raw power and baseline both are affected by aliasing in the same amount. The strong peaks at 1 Hz and 2 Hz disappear traceless in the difference (the power noise spectrum), proving the efficiency of the method.

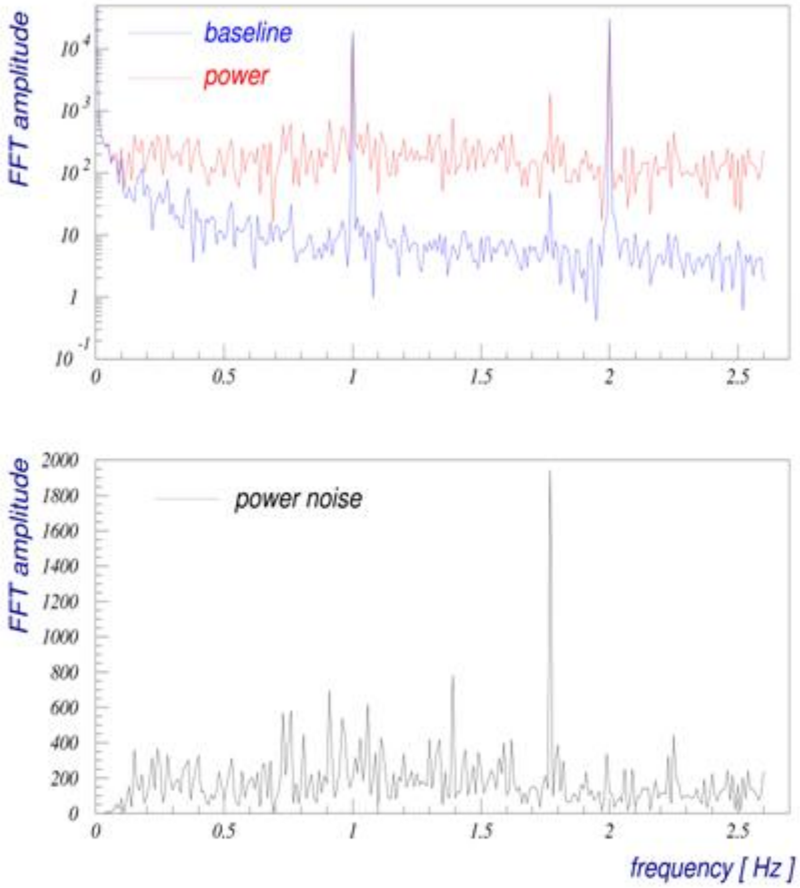

Figure 4: Fourier transform of reactor power, baseline and noise. It can be seen that the raw power and baseline both are affected by aliasing in the same amount. The strong peaks at 1 Hz and 2 Hz disappear traceless in the difference (the power noise spectrum), proving the efficiency of the method.

V. CONCLUSIONS

For low frequency power noise monitoring it is in certain contexts impossible to remove aliasing frequency components, pre-sampling. Although aliasing collision is not present in the high end of the spectrum, close to f_{Ny} - this being a naturally free region, in the low region the post-DAQ processing method here presented of raw-baseline subtraction is the only effective means of aliasing collision suppression. Such context appears for instance when the sensors delivering the data have saturation and blind-times after high-pulses (for instance of radiation), acting as an effective sampling that is not avoidable through filters. Also, very-low pass filters are difficult to design for 2.5 Hz in the case presented. Digital filters need high sampling rates to avoid the exact condition that is being presented. Analog active filters have a high-Q, thus broad band signals have components that bypass them. Passive very-low pass filters are extremely bulky.

The method presented is feasible in real-time, via a flash updating procedure of the data on the fly, allowing complex baseline polynomials that in *long double* precision rank in order up to k = 40/ln(z), where 2z is the number of time-bins of the fit interval.

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