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Support to the identification of anomalies in an external neutron source using Hurst Exponents

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A new methodology is proposed here to identify anomalies in the neutron flux as a result neutron production trips in an Accelerator Driven System - ADS type reactor. This methodology is based on the calculation of Hurst exponents, where the neutron flux as monitored in the reactor core is treated as a temporal series. In several recent articles, related to fractional diffusion, the Hurst exponent is used as an estimate for the order of the fractional derivative. Our object of study considered a reactor based on the Myrrha simulated with the Serpent Monte Carlo code for two kinds of trips occurred in the production of neutrons, as follows: a Peak of Production (PP), the Unprotected* Accelerator Beam Overpower (UABO), and the spurious Beam Trip (BT). In order to estimate the Hurst exponent it was used two different methods, namely the Rescaled Range Analysis (R/S) and the Detrended Fluctuation Analysis Method (DFA). The results obtained showed that the R/S methodology had some advantages in a comparison with the DFA in indicating the occurrence of those anomalies. Also being able to provide a scale for the assessment of the intensity of the trip occurred, showing to be an useful tool to support anomaly identification in the neutron flux of ADS reactors.

1. Introduction

Amongst 4th-gen reactor designs the one the stands out for its capability to generate power from transmuting heavy elements with a long half-life, and thus reducing the inventory of radioactive materials, is the Accelerator-Driven System (ADS). ADS reactors have a sub-critical core guided by a beam high-energy protons generated by a linear accelerator. These protons, as they collide with an appropriate target, generate, from spallation reactions, the neutrons needed to keep the fission rate of the cores under control, to obtain power (Mukaiyama et al., 2001). Following the spallation reaction the neutrons are diffused in the reactor core, providing a power production dynamic that is being widely studied as this proposal will still be used in a large scale.

One of the goals of this paper is to identify, through the neutron flux, the instant when anomalies of the UABO and BT kind take place (Suzuki et al., 2005; Vandeplassche et al., 2011). In order to identify an anomaly in the neutron flux a different approach is presented here that allows considering small statistical fluctuations. For that, we will use the time series studies initially done by Hurst et al. (1966). These methods will be used to identify trends in time series and to classify the diffusion processes occurred in this type of system. The evaluation of the Hurst Exponent will be made from two different calculation methods, namely: Rescaled Square (R/S) (Hurst et al., 1966) and Detrendend Fluctuation Analysis (DFA) (Peng et al., 1994).

To that end we simulated a Myrrha Reactor, using the Serpent Reactor Physics code, after Bruyn et al. (2007), considering a neutron source that presents anomalies of the UABO and BT kinds. We resorted to the Serpent code as it allows the implementation of several counters on any surface or in any region of the reactor under study. With it one can get the neutron flux during the operation of the reactor at hand with detail.

Section 2 describes the methodology used to calculate the Hurst Exponents, using the R/S and DFA methods. Section 3 describes the simulations we carried out. Section 4 provides the preliminary results as obtained in the identification of UABO and BT anomalies,

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whilst Section 5 provides the conclusions to this work.

2. Methodology

The neutrons have a random trajectory and the stochastic formulation of these transport phenomena, as regards a random path, as well as the description through a mathematical model executed through the diffusion equation are two fundamental concepts in the theory of diffusion. The linear dependency on the temporal growth of the average quadratic displacement of the particles $\langle x^2(t)\rangle \propto tS$ or, in an equivalent manner, of variance, is a characteristic of Brownian motion and therefore of regular diffusion. The characteristic of anomalous diffusion is generally a non-linear growth of the variance in time, that is, $\langle x^2(t)\rangle \propto t^\alpha S$. Several works on anomalous diffusion in the field of reactor Physics can be found in the literature (Espinosa-Paredes et al., 2011; Vyawahare and Nataraj, 2013) that discuss possible advantages in relation to conventional diffusion equations based on integer order derivatives, and consider an infinite speed of the neutrons, and have a limited spatial application.

With this, it is necessary to use a tool capable of estimating the value of α. In a recent article, Hahn et al. (2010) proposed that the order of the fractional derivative is twice that of the Hurst exponent, and Espinosa-Paredes et al. (2006) used the DFA methodology directly, to obtain the order of the fractional derivative without going much deeper in it. The original problem as studied by Hurst was linked to the construction of dams in the River Nile and for that he monitored its periods of greater and smaller flow. Hurst wanted to establish the ideal volume for water storage in a reservoir, based on the data for water as required in time.

Let's call the Hurst exponent in a generic way as H. Two methodologies are presented below to estimate this exponent, as used in this article.

2.1. The R/S method

The problem tackled in Hurst's analysis consisted of determining a model for a reservoir, based on the records for output flow for a given lake so that the reservoir neither emptied completely nor overflowed. In a given year t, the lake receives a random influx of water $\xi(t)$ as a result of the rainfall. A mean value for the water flow rate $\langle\xi\rangle_\tau$ has to be released by the reservoir so to maintain a certain volume of water in storage. Therefore, the mean value for the output flow rate in relation to the time frame should be:

$$\langle\xi\rangle_\tau = \frac{1}{\tau}\sum_{t=1}^{\tau}\xi(t), \tag{1}$$

with $X(t,\tau)$ for accumulated discharges, obtained by subtracting the value of the discharge from its mean value, that is:

$$X(t,\tau) = \sum_{u=1}^{t}\{\xi(u) - \langle\xi\rangle_\tau\}(1 \le t \le T). \tag{2}$$

The difference between the maximum and minimum discharge numbers, X, is the average for the R (range).

$$R(\tau) = \max_{1\le t\le\tau}X(t,\tau) - \min_{1\le t\le\tau}X(t,\tau), (1 \le t \le \tau), \tag{3}$$

where $R(\tau)$ is the variation between the maximum and the minimum volumes of the reservoir, and τ is the time frame. Thus, R is the storage capacity needed to keep the minimum discharge volume in the period so to meet the requirement that the reservoir neither overflows nor dries out completely.

Hurst studied many natural phenomena, using the a-dimensional ratio R/S where S is the standard deviation, that is, the root square of the variation, as provided by:

$$S = \left(\frac{1}{\tau}\sum_{t=1}^{\tau}\{\xi(t) - \langle\xi\rangle_\tau\}^2\right)^{\frac{1}{2}}. \tag{4}$$

Hurst found that the a-dimensional ratio R/S allows comparing the re-sizing of several temporal series and that such a re-sizing can be very well described by a law of power as follows:

$$\frac{R}{S} = kN^H, \tag{5}$$

where: N is the time interval for the observations, H is the estimate for Hurst's Exponent as calculated from the R/S method and k is a constant.

This method is very well established in the literature and has applications in many areas of knowledge, such as the stock market (Sánchez et al., 2015), hydrology studies (Koutsoyiannis et al., 2011), and on multi-phase flow systems (Li et al., 2013).

2.2. DFA - Detrended Fluctuation Analysis

The determining of Hurst's exponent has been widely studied, giving rise to a large number of methodologies for the analysis of temporal series, including the so-called Detrended Fluctuation Analysis (DFA) (Peng et al., 1994). A brief description of this technique is given below:

i) From the original series one obtains the integrated series;

$$x(i) = \sum_{i=1}^{k}[y_k - \langle y\rangle]. \tag{6}$$

The integrated series is divided into N windows with n elements in each window;

ii) The trend of the series is removed by reducing from the original series the polynomial $p_\nu(i)$ as adjusted in the window;

$$x_n(i) = x_i - p_\nu(i). \tag{7}$$

iii) The variance for each segment is calculated;

$$F_n(\nu) = \langle x_n(i)\rangle = \frac{1}{n}\sum_{i=1}^{n}x_n[(\nu-1)n + i]. \tag{8}$$

iv) The average is calculated for all the segments and the square root is found to obtain the DFA fluctuation function:

$$F(n) = \sqrt{\frac{1}{N}\sum_{\nu=1}^{N}(F_n(\nu))^2}. \tag{9}$$

This calculation is repeated for all possible window sizes, from $n_{max} = N/4$ to $n_{min} = 5$. Usually $F(n)$ increases with the number of n window elements. After that, a graph $\log(F(n))$ x $\log(n)$ is plotted and the linear coefficient of this graph determines the self-similarity parameter ω in the shape of an exponent N^H, where H is Hurst's Exponent, as estimated from the DFA methodology.

For a short interval or for situations where the points are not correlated, one obtains $H = 0.5$ or 'white noise'. On the other hand, if $H < 0.5$ the correlation in the signal is anti-persistent, that is, an increase is probably followed by a decrease and vice-versa. For