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DECAY RATIO STUDIES IN BWR AND PWR USING WAVELET

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Decay Ratio Studies in BWR and PWR using *Wavelets*

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Abstract

The on-line stability of BWR and PWR is studied using the neutron noise signals as the fluctuations reflect the dynamic characteristics of the reactor. Using appropriate signal modeling for time domain analysis of noise signals, the stability parameters can be directly obtained from the system impulse response. Here in particular for BWR, an important stability parameter is the decay ratio (DR) of the impulse response. The time series analysis involves the autoregressive modeling of the neutron detector signal. The DR determination is strongly effected by the low frequency behaviour since the transfer function characteristic tends to be a third order system rather than a second order system for a BWR. In a PWR low frequency behaviour is modified by the Boron concentration. As a result of these phenomena there are difficulties in the consistent determination of the DR oscillations. The enhancement of the consistency of this DR estimation is obtained by wavelet transform using actual power plant data from BWR and PWR. A comparative study of the estimation with and without *wavelets* are presented.

Keywords: BWR Stability Analysis, PWR Stability Analysis, Reactor Noise, Wavelet,
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I Introduction

Stability is an important concern in control and operation of a dynamic process system as a nuclear reactor. From the design viewpoint, such stable systems may be conceived that they can exercise some incidental operational occurrences due to situations called *dynamic instabilities*. Basically, this is due to time lag involved in a reactivity feedback. Nevertheless for PWRs, the stable regions established by the reactivity coefficients are rather well defined and the reactivity disturbances lead to a limited power response. Some instability concerns might be due to low Boron concentrations at the end of the fuel cycle. However, the issue is essentially important for boiling water reactors due to basically interaction between thermal hydraulics and neutronics. This is caused by the reactivity effect of steam bubbles and the time lag between a reactivity change and the corresponding change in steam void fraction due to power changes. An addition to this, the two-phase-flow instabilities should be mentioned resulting in a peculiar thermo-hydraulic behaviour termed as density-wave oscillations.

Motivated by the stability considerations briefly mentioned above, an amount of research has been reported in the literature especially for BWRs more than for PWRs. Two aspects can be distinguished: There are articles which describe the early primary investigations to identify the underlying physics of the phenomena leading to instabilities. On the other hand, it is important to have the necessary information on the causes of instability and to establish suitable means to monitor these instabilities even in real-time. An important outcome of these articles is that reactor neutron noise signals can be used for the stability analysis and monitoring in such a way that the perturbation of the system is circumvented. This means, continuous monitoring by these signals is possible. In this context, the conventional approach is the utilization of the advanced signal modeling techniques. In the last two decades, with the aid of computer technology, such methods are intensively used in nuclear industry not only for reactor stability but also for general reactor analysis. The neutronic fluctuations reflect the dynamical characteristics of the reactor and in particular in BWRs; the steam content change in the core excites the system. The early researches with noise signals revealed that the BWR can reasonably be characterized as a second-order damped system with relevant characteristic quantities being defined.

The time series model is a causal representation of the dynamic behaviour of the system in a way that the dynamic character of the plant is effectively represented. Here, an important stability parameter is the decay ratio (DR) of the impulse response. Decay ratio is defined as the ratio of two consecutive maxima of the impulse response. For a second-order system, this ratio is constant during the course of the impulse response and it is also equal to two consecutive maxima of the autocorrelation function (ACF). Exploiting these features, the stability determination for BWRs is studied by several authors with a qualified success [1–3]. The same applies to PWRs [4]. In particular, the qualification stems from the fact that, a reactor is not strictly a second-order system and even its global characteristic is more third-order rather than second-order for a BWR. From this viewpoint the validity of a second-order system assumption for PWR can hardly be justified. However, another important factor in such determinations is the method in use. Among the outstanding methods, time-series analysis, spectral decomposition and neural networks should be mentioned. To pin down the problems a brief introduction here is appropriate.

The majority of time series analysis methods uses an autoregressive (AR) model for the impulse response acquisition where the signal is modeled for model order p and $p+1$ as

$$y_k = -\sum_{i=1}^{p} a_i y_{k-i} + \epsilon_p(k) \tag{1.1}$$

$$y_{k+1} = -\sum_{i=1}^{p+1} a_i^* y_{k-i} + \epsilon_{p+1}(k) \tag{1.2}$$

where a_i and a_i^* are the model parameters which are known as AR parameters; $\epsilon_p(k)$ and $\epsilon_{p+1}(k)$ are white noise sequences. If we multiply Eq (1.1) and Eq (1.2) by y_k and take the average, we obtain after some arrangements

$$\sigma_p^2 - \sigma_{p+1}^2 = -\sum_{i=1}^{p}(a^* - a_i)R(i) - a_{p+1}^* R(p+1) \tag{1.3}$$

The AR coefficients a_i^* can be expressed in terms of a_i by means of Levinson-Durbin recursive algorithm. The recursion is of the form

$$\begin{aligned} a_i^* &= a_i - g_{p+1}\, a_{p+1-i} \qquad i = 1, \dots, p \\ a_{p+1}^* &= -g_{p+1} \end{aligned} \tag{1.4}$$

where $a_0 = 1$ and g_{p+1} is known as reflection or parcor coefficient defined by

$$g_{p+1} = \frac{\sum_{i=0}^{p} a_i R(p+1-i)}{\sum_{i=0}^{p} a_i R_i} = \frac{\sum_{i=0}^{p} a_i R(p+1-i)}{\sigma_p^2} \tag{1.5}$$

so that the residual variances σ_p^2 and σ_{p+1}^2 are related to each other through the reflection coefficient of the form

$$\sigma_{p+1}^2 = \sigma_p^2(1 - g_{p+1}^2) \qquad p = 0, 1, 2, \dots \tag{1.6}$$

Above, σ_0^2 is the variance of the incoming raw data sequence. It is noteworthy to mention that, since both σ_{p+1}^2 and σ_p^2 are positive, it follows that the factor $(1 - g_{p+1}^2)$ will be positive and less than unity. It represents the improvement in the prediction afforded by using a predictor of the order $p + 1$ instead of order p. Another point noteworthy is that g_{p+1} has a magnitude less than one and this is an indication of the stationarity of the signal.

The estimation of the impulse response function on the basis of this model i.e., univariate AR, is given by

$$h_i = \sum_{k=1}^{j} a_{j,k} h_{i-k} \tag{1.7}$$

the initial conditions being set to

$$h_m = 0 \quad \text{for} \quad m < 0 \quad \text{and} \quad h_0 = 1 \tag{1.8}$$

For DR estimation, the problems encountered here are the excessive model orders (model order of 50 for a second-order system, for instance) due to low frequency effects in the measured spectrum. The same problem applies to the autocorrelation and the spectral decomposition analyses methods using multivariate AR or fast Fourier transform analysis. This is because of the model errors and the measurement errors and the systematic errors introduced during the signal processing (windowing in spectrum estimation, finite block size effects in correlation estimation, for instance). Concerning neural networks, the case is not fully under control due to the lack in the actual data needed for training. Added to this, the degree of the nonlinearity of the neural structure depends on the number of hidden layer nodes. This means that matching of the nonlinearity of the neural structure to the nonlinearity of the functional relationship to be established is an important issue for the performance of this approach. Some elaborations are imperative.

From above discussion, one may conclude that the stability determination based on the decay ratio computation apparently is not complete satisfactory, due to the fact that the method may not be always conclusive due to both model errors and measurement errors. Reduction of these errors needs long measurements and careful signal processing. This report describes a novel utilization of neutron noise signals for stability monitoring. In this novel approach, a new signal analysis method called *wavelets* is used. *Wavelets* collectively indicates a new technology in the field of signal analysis and its use in nuclear technology is demonstrated [5] and suggested [6].

The organization of the paper is as follows. In Sec.II, wavelet analysis is briefly outlined; basic definitions and properties related to wavelet analysis are given including discrete bases for signal decomposition and reconstruction which constitute the essential signal processing part of the work. In Sec.III, a general wavelet approach for stability analysis is described. Section IV describes the application of the method to BWR and PWR signals. Some concluding remarks are given in Sec.V.

II Wavelet Analysis

In contrast to Fourier analysis in frequency domain and time series analysis in time domain, wavelet analysis is used to analyze the signal in both, time and frequency domains [7–9]. By doing so, a signal is decomposed to some components corresponding to different frequency ranges. Each component is further considered with a resolution matched to its scale. The continuous wavelet-transform (CTWT) is defined as the inner product of f(t) with the basis functions

$$\Psi_{a,b}(t) = a^{-\frac{1}{2}}\Psi\left(\frac{t-b}{a}\right) \tag{2.1}$$

so that

$$CTWT_f(a,b) = a^{-\frac{1}{2}}\int_{-\infty}^{\infty}\Psi\left(\frac{t-b}{a}\right)dt \tag{2.2}$$

where Ψ is referred to as *mother wavelet* and a and b are, respectively, *scale* and *shift* parameters. The Fourier coefficients of the wavelet transform are obtained from the equation

$$W(a,b) = a^{\frac{1}{2}}f(\omega)\Psi(a\omega) \tag{2.3}$$

The computation of the continuous wavelet transform by the discretization of the integral term is not a general approach due to the high cost of the computations and the large errors arising at small scales. For continuous time computation, generally Eq (2.3) is used.

The basis functions $\Psi_{a,b} \in L^2(R)$ are real and oscillating. They are called *wavelets* and can be viewed as contracted and shifted versions of the function $\Psi_{a,b}(t)$. The function $\Psi(t)$ has to satisfy the admissibility condition

$$C_\Psi = \int_0^{\infty}\frac{|\Psi(\omega)^2|}{\omega}d\omega < \infty \tag{2.4}$$

in order to be able to reconstruct $f(t)$ from its CTWT.
$\Psi(\omega)$ above is the Fourier transform of $\Psi(t)$. The reconstruction formula is

$$f(t) = \frac{1}{C_\Psi}\int_{-\infty}^{\infty}\int_0^{\infty} CTWT_f(a,b)a^{-1/2}\Psi\left(\frac{t-b}{a}\right)a^{-2}\,da\,db \tag{2.5}$$

In $CTWT_f(a,b)$ the parameters a, b vary continuously. It is possible to discretize the values for a and b, while still being able to reconstruct the signal from its transform. For this we substitute

$$a = a_0^i \quad , \quad b = jb_0a_0^i \quad , \quad i,j \in Z \quad , \quad a_0 > 1 \quad , \quad b_0 \neq 0 \tag{2.6}$$

The corresponding wavelets for the discretized a and b are

$$\Psi_{i,j}(t) = a_0^{-i/2}\,\Psi(a_0^{-i}t - j) \tag{2.7}$$

so that the wavelet transform becomes

$$(W_\Psi f)_{i,j} = d_{i,j} = \int_{-\infty}^{\infty} a_0^{-i/2}\,\Psi(a_0^{-i}t - j)\,f(t)\,dt \tag{2.8}$$

In order to clearly present what role wavelets play in the stability analysis, first we recall the mathematical foundations i.e., the multiresolution analysis and orthogonal wavelet bases.

A multiresolution analysis of a function f consists of the estimation of a series of functions f_j, corresponding with different representations of that signal where j represents the detail index of size 2^{-j}. These estimates converge to f when j tends to infinity. This can be described best by the theory of function spaces. A multiresolution analysis is a description of $L^2(R)$ as a hierarchy of embedded subspaces V_m which have intersection $\{0\}$ and for which the limit of their union is $L^2(R)$; namely

$$\ldots \subset V_2 \subset V_1 \subset V_0 \subset V_{-1} \subset V_{-2} \subset \ldots$$

verifying the following properties [7–9]:

(i) $\cap_{j\in Z} V_j = \{0\} \qquad \cup_{j\in Z} V_j = L^2(R)$

(ii) $f \in V_j \iff f(2^{-j}.) \in V_{j+1} \quad , \quad j \in Z$

(iii) $f \in V_0 \iff f(. - k) \in V_0 \quad , \quad k \in Z$

(iv) There exists $\Phi \in V_0$ so that $\{\Phi(t-k)\}_{k\in Z}$ is an orthonormal base of V_0.

As the functions $\Phi_{0,j}(t)$ form an orthonormal basis for V_0, it follows that the functions

$$\Phi_{i,j}(t) = 2^{-i/2}\,\Phi(2^{-i}t - j) \tag{2.9}$$

constitute an orthonormal basis for V_i. These basis functions are referred to as scaling functions since they build up scaled versions of the functions in $L^2(R)$. From the multiresolution analysis introduced one realizes that a function $f(t)$ in $L^2(R)$ can be seen as a successive approximation by functions $f_i(t)$ in V_i. Hence, the function $f(t)$ is the limit of the approximations $f_i(t) \in V_i$ for i to $-\infty$, namely

$$f(t) = \lim_{i\to-\infty} f_i(t) \tag{2.10}$$

This creates the possibility to examine the function or signal at several resolutions or scales. The variable i indicates the scale and is therefore called *scale factor*. If the scale factor is high, this means that the function in V_i is a coarse approximation of $f(t)$, details are being neglected. On the contrary, if the scale factor is low, a detailed approximation of $f(t)$ is achieved. All functions in V_i can be represented using linear combinations of the scaling functions. Hence one can view that , $f_i(t)$ is an orthogonal projection of $f(t)$ onto V_i, of the form

$$f_i(t) = \sum_j < \Phi_{i,j}(t), f(t) > \Phi_{i,j}(t) \; = \sum_j c_{i,j}\Phi_{i,j}(t) \tag{2.11}$$

Since

$$\Phi(t) = \Phi_{0,0}(t) \in V_0 \subset V_{-1}$$

For a specific sequence h_j, we can write

$$\Phi_{0,0}(t) = 2^{\frac{1}{2}} \sum_j h_j \Phi_{-1,j}(t) = 2 \sum_j h_j \Phi(2t - j) \tag{2.12}$$

so that $\Phi_{0,0}(t)$ is a solution of a two-scale difference equation indicating the close relationship between the function $\Phi(t)$ and the sequence h_j.

In the above definition we can assume that the space $L^2(R)$ is built up the set of *rings* that are differences between two consecutive spaces. These difference spaces are denoted by W_i with respect to V_{i-1} so that

$$V_{i-1} = V_i \oplus W_i \tag{2.13}$$

$$\cap_{i \in Z} W_i = \emptyset \qquad \cup_{i \in Z} W_i = L^2(R) \tag{2.14}$$

where $\oplus$ indicates the summation of the orthogonal spaces. The W_j spaces verify the following properties.

(i) $f \in W_j \Longleftrightarrow f(2^{-j}.) \in W_0 \quad , \quad j \in Z$

(ii) $\Psi \in W_0 \Longleftrightarrow \Psi(. - k) \in W_0 \quad , \quad k \in Z$

(iii) W_i is orthogonal to W_j for $i \neq j$

(iv) $\oplus_{j \in Z} W_j = L^2$

Let $\Psi(t) = \Psi_{0,0}(t)$ be a basis function of W_0. Since $\Psi_{0,0}(t) \in W_0 \subset V_{-1}$ we can write

$$\Psi_{0,0}(f) = 2^{\frac{1}{2}} \sum_j g_j \Phi_{-1,j}(t) \tag{2.15}$$

for a certain sequence of g_j. The functions $\Phi_{i,j}(t)$ are shifted and dilated versions of each other. Therefore, we can also define the functions $\Psi_{i,j}(t)$ which are shifted and dilated versions of one prototype function $\Psi(t)$, of the form

$$\Psi_{i,j} = 2^{-i/2}\, \Psi(2^{-i}t - j) \tag{2.16}$$

The functions $\Psi_{i,j}(t)$ are identical to the wavelets introduced earlier after the discretization of Eq. (2.6). The parameter a_o in Eq. (2.7) is fixed and equal to 2 in this case. They form an orthonormal basis for $L^2(R)$.

The wavelet transform algorithm carries out the multiresolution decomposition as follows. Let Φ be the scaling function. At step j, we have the signal f_j which belongs to the space of approximations V_j and its coefficients $c_{j,k}$ on the bases of V_j. Then, using the equation $V_{j-1} = V_j \oplus W_j$ we compute its projection f_{j-1} on V_{j-1} where, in particular, $d_{j-1,k}$ are coefficients on the bases of W_{j-1} and $c_{j-1,k}$ are coefficients on the bases of V_{j-1}. The coefficients $c_{j-1,k}$ and $d_{j-1,k}$ are obtained by respectively applying a low-pass filter H and a high-pass filter G to the sequence $c_{j-1,k}$ [5].

III Improved Decay-Ratio Estimation by Wavelet Analysis

The wavelet approach for stability analysis can be applied on the low frequency effects in the power spectral density of the signal from the neutron detectors. Particularly, for BWRs the DR determination is strongly effected by the low frequency behaviour since the transfer function characteristic tends to be a third order system rather than a second order system. The same effect occurs in a less extend in PWRs, being the effect attributed to diminished Boron concentration at the end of the fuel cycle. By means of wavelet transform the low frequency part of the spectrum is replaced by a flat spectrum, i.e., gaussian white, in order to eliminate the low frequency effects. To this end, initially, a discrete band-limited white noise signal is considered. This can easily be formed by means of a suitable algorithm and a built-in noise generator in a computer. This signal is decomposed by means of wavelet transform into several signal components matching to their individual multiresolution scale of frequency. In the same way the detector signal is subjected to the same wavelet decomposition as well. Depending on the width of the low frequency part one would intend to replace, the scales subject to this due replacement, is substituted with the counterpart of that from the white noise. The computation is rather straightforward due to one-to-one replacement. However, not to modify the original signal beyond the intention, perfect reconstruction from the wavelet analysis is a requirement. Therefore here in the analysis, orthogonal wavelets, specifically Daubechies's wavelets with compact support length of 12, are used.

IV Application to BWR and PWR

The wavelet-based decay ratio estimation described above is implemented to the recorded data from two operating nuclear power plants in the Netherlands, namely, the Dodewaard BWR (58 MWe) and the Borssele PWR (450 MWe). Data have been collected with the on-line data acquisition and processing systems at the Netherlands Energy Research Foundation (ECN) site.

The Dodewaard BWR is a small-sized BWR with natural convection circulation and has been operating since 1968 by NV-GKN (Gemeenschappelijk Kerncentrale Nederland). To test the DR investigations using on-line DR measurements a demonstration experiment with ECN on-line data acquisition and data analyses system, has been carried out at the Dodewaard reactor (on 8 November 1989). Among the various reactor signals that were measured, signals from four ex-core neutron detectors of safety channels have been used for real-time DR calculation. The Dodewaard reactor is a very stable BWR. During a complete fuel cycle , the DR varies between 0.10 – 0.35. The monitored signals, spectra, and impulse responses derived by an univariate autoregressive method and the DR in real-time have been displayed to the reactor supervisors and to the members of Dutch Nuclear Safety Authority [10]. Thereafter, a stability monitoring system based on real-time on-line decay-ratio computation is thus realized and launched for operation for actual use with endorsement. In this wavelet application, a small part of the recorded noise signals of the ex- core neutron detector (N-6) from that experiment is used. The sampling period of the data used in the experiment was selected as 16 (s/s). The analysis of the same data with wavelet is shown in Fig.1a-d where respectively, impulse response, step response, power spectrum from AR modeling and DR estimation are shown. The model order in this case as low as 6, the data block length is 128 which is intentionally low for real-time and on-line DR estimations. The decay ratio resulted from this analysis through the wavelet application is verified with the on-line DR estimation [10]. The functionality of wavelet analysis and the improvement achieved by wavelet are clearly demonstrated.

The outcomes of the same studies but applied for PWRs is presented in Fig.2a-f. The plant considered is the Borssele NPP in the Netherlands. The Borssele PWR is a two loop system built by KWU and operated by N.V. Electriciteits-Productiematschappij Zuid Nederland EPZ since 1973. On-line experiments are carried out since 1982 for monitoring, surveillance and diagnostics research and implementation purposes [11]. For this wavelet investigation we have used noise signals of the ex-core neutron detector (D621) during the nominal reactor power at the beginning of a operating cycle (Boron concentration at 910 ppm) and at the end of a fuel cycle (20 ppm). Noise data from the sensor signals are sampled with 8 samples/second. The illustrations show two different operational situations; namely operation data at the beginning of the cycle and at the end of the cycle. Wavelet conditions and AR signal modeling conditions are kept the same as those for BWR studies described. There is no obvious change in wavelet due to the intrinsic flat spectrum of a PWR at low frequencies. The decay ratio is found to be relatively very low as one would expect.

V Concluding Remarks and Conclusion

Real-time decay ratio estimation is important for monitoring the stability of a BWR. Among the decay ratio estimations by conventional means i.e., autocorrelation (ACF), spectral decomposition and time-series signal modeling, only the latter is of interest while the others are more suitable for off-line estimations. Neural network approach is quite suitable for real time estimations but the method is not mature enough for conclusive assessments. In the time-series signal modeling approach a block of data is considered at each time for modeling and followed by DR. Statistical variations play an important role on the results of estimations. The case is aggravated in the case the data block is short. In contrast with this, a short length of the data is preferable for real-time operations. Referring to these conflicting qualifications accurate estimates by signal modeling becomes an issue of optimal design of a measurement. The case is more hampered if the model errors are also important factor on the parameter determination as this is the case in DR estimation due to second-order system approximation. Referring to these, the estimation is highly improved by the utilization of wavelet transform for BWR case. For PWR, such improvement is found to be not obvious for the same conditions used during the investigations for BWR. However, for increased block length of data, the DR estimations are found to be improved and in this case also for PWRs, wavelets can still be of substantial help for accurate estimations.

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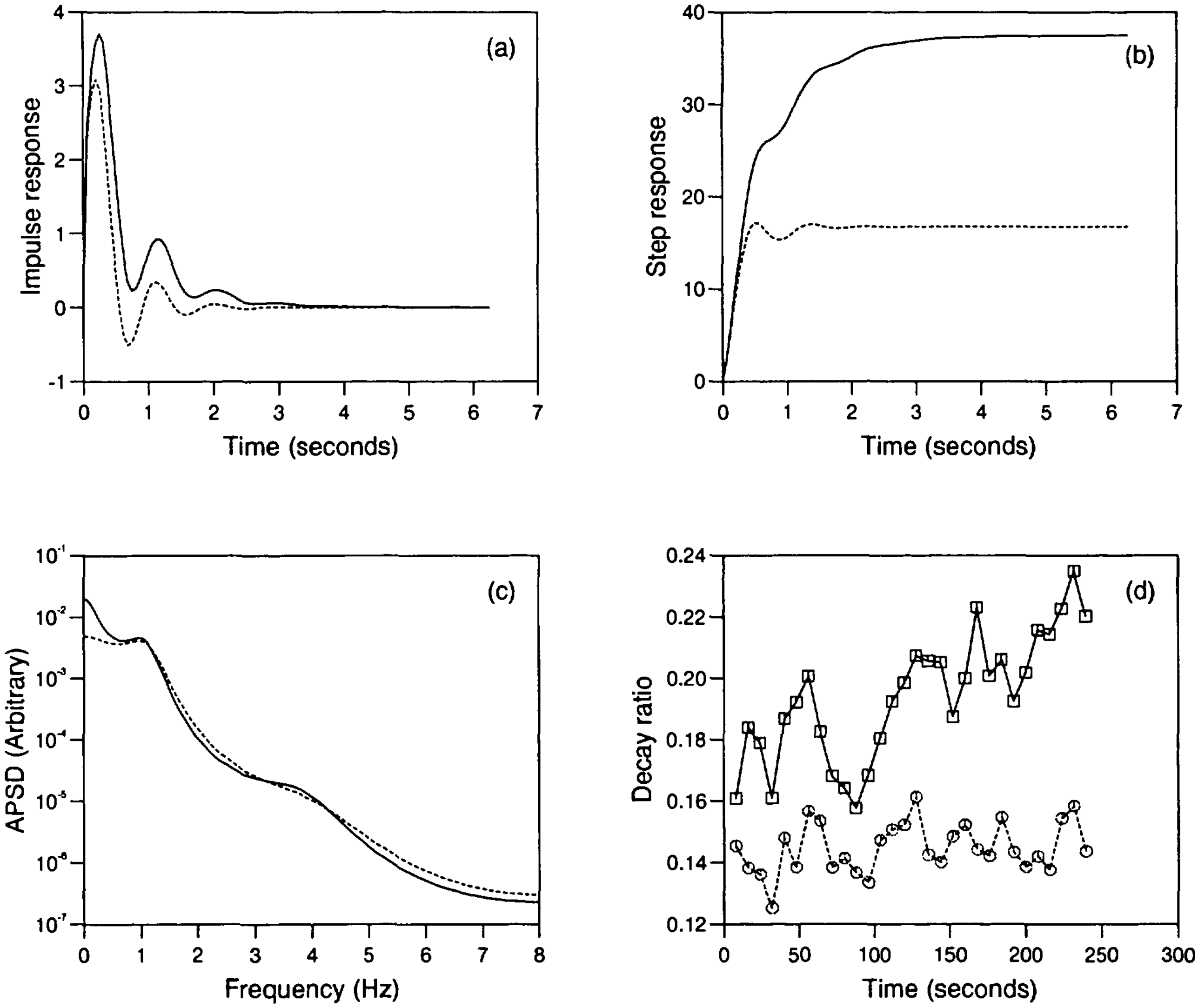

Fig. 1: *Wavelet approach for DR estimation of BWR. Broken lines indicate the outcomes of the conventional analysis counterpart. (a) Impulse response, (b) Step response, (c) Power spectrum, (d) Decay ratio.*

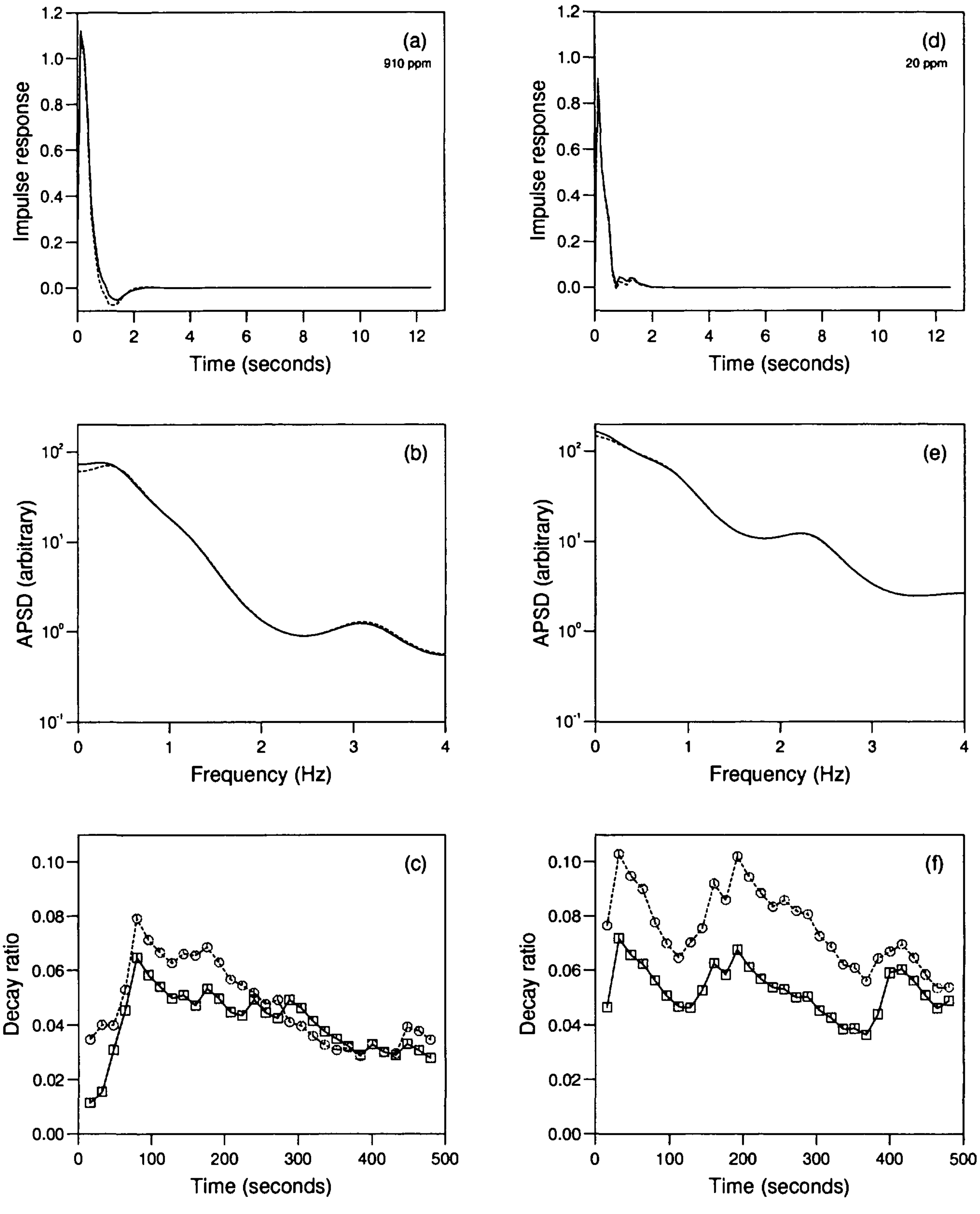

Fig. 2: *Wavelet approach for DR estimation of PWR. Broken lines indicate the outcomes of the conventional analysis counterpart. (a) Impulse response, (b) Power spectrum, (c) Decay ratio abtained at the beginning of fuel cycle. The Figs. d,e,f are obtained at the end of the fuel cycle and they are the counterpart of Figs. a,b,c respectively.*