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A PHYSICAL MODEL OF NONLINEAR NOISE WITH APPLICATION TO BWR STABILITY

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Historically, the study of stochastic processes for power reactor surveillance and diagnostics has been based on the linearization of the governing equations. This approach has proven to be adequate for many problems; however, for some conceivable situations, such as boiling water reactors (BWRs) close to the boundary of instability, the linear assumption may be violated due to possible large power oscillations. The purpose of this paper is to study the influence of nonlinearities on BWR neutron noise and its effects on stability.

The physical model was described by the following equations:

$$\frac{\partial n}{\partial t} = \frac{\rho-\beta}{\Lambda} n + \lambda c + \frac{\rho}{\Lambda} \tag{1}$$

$$\frac{\partial c}{\partial t} = \frac{\beta}{\Lambda} n + \lambda c \tag{2}$$

$$\frac{\partial T}{\partial t} = Q - a_3 T \tag{3}$$

$$\frac{\partial^2 \rho}{\partial t^2} + a_2 \frac{\partial \rho}{\partial t} + a_1 \rho = T \tag{4}$$

$$Q = K[n + f(t)] \tag{5}$$

which includes: (a) one delayed-group point kinetics, Eqs. (1) and (2); (b) the fuel, in a single-node approximation, Eq. (3); and (c) the thermal-hydraulic loop, which has been reduced to a second-order equation for the feedback reactivity, Eq. (4). This last equation has been derived from a two-node approximation of the continuity and energy

equations. The power generation, Q, is assumed to be proportional to the neutron density plus a band-limited Gaussian white noise, f(t), acting as the driving source, Eq. (5); the constant K is an adjustable feedback gain that determines the stability of the linear system. The critical value at which the linearized system becomes unstable is Kc = 0.08912. The parameters $a_1 = 6.8166\ s^{-2}$, $a_2 = 2.2492\ s^{-1}$, and $a_3 = 0.2325\ s^{-1}$ have been obtained from a detailed calculation for a typical BWR at operating conditions close to instability using the code LAPUR.[1,2] All state variables are perturbations around equilibrium; n(t) and c(t) are normalized to the steady-state neutron density, and $\beta = 0.0056$, $\lambda = 0.08\ s^{-1}$, and $\Lambda = 4. * 10^{-5}$ s.

An equation similar to (4) was formulated by Thie[3] and utilized by Akcasu[4] to explain oscillations in BWRs. However, the present study exhibits two distinct differences compared to the Thie formalism: (a) The driving noise, T(t), is a function of the power so that the reactivity coupling in Eq. (1) is nonlinear, and (b) all the coefficients are deterministic.

The set of equations was solved numerically using an A-stable routine.[5] Two parameters were varied: the feedback gain, K, and the variance of the driving noise source. The generated power traces, n(t), were Fast Fourier Transformed to obtain power spectral densities (PSDs).

The results show that for stable systems, K<Kc, the PSDs exhibit a single peak at the characteristic frequency as predicted by the

linearized studies;[1],[2] however, as K approaches Kc while maintaining the driving source variance constant, the PSDs develop peaks at the harmonics of this fundamental frequency. For K>Kc, the power oscillations increase in time and eventually reach a limit cycle, with an enhancement of the harmonic components of the PSD as seen in Fig. 1.

The development of the limit cycle is shown in Fig. 2. Here, the system was originally in equilibruim. When a zero mean white noise was applied, the magnitude of the oscillations increased initially until it reached a limit value. This limit value is independent of the magnitude of the driving noise variance, as expected.[6]

In conclusion, within the framework of the present model it is shown that the reactor cannot be unstable in the linear sense, but rather it executes limited power oscillations of a magnitude that depends on the operating conditions. The onset of these oscillations can be diagnosed by the decrease in stochasticity in the power traces and by the appearance of harmonics in the PSD.

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Fig. 1. Power Spectral Densities (PSDs) of the neutron response of a typical BWR as a function of frequency for three values of the feedback gain: (a) K = 0.888, (b) K = 0.089, and (c) K = 0.090, where PUDC means Per Unit DC and Kc = 0.08912.

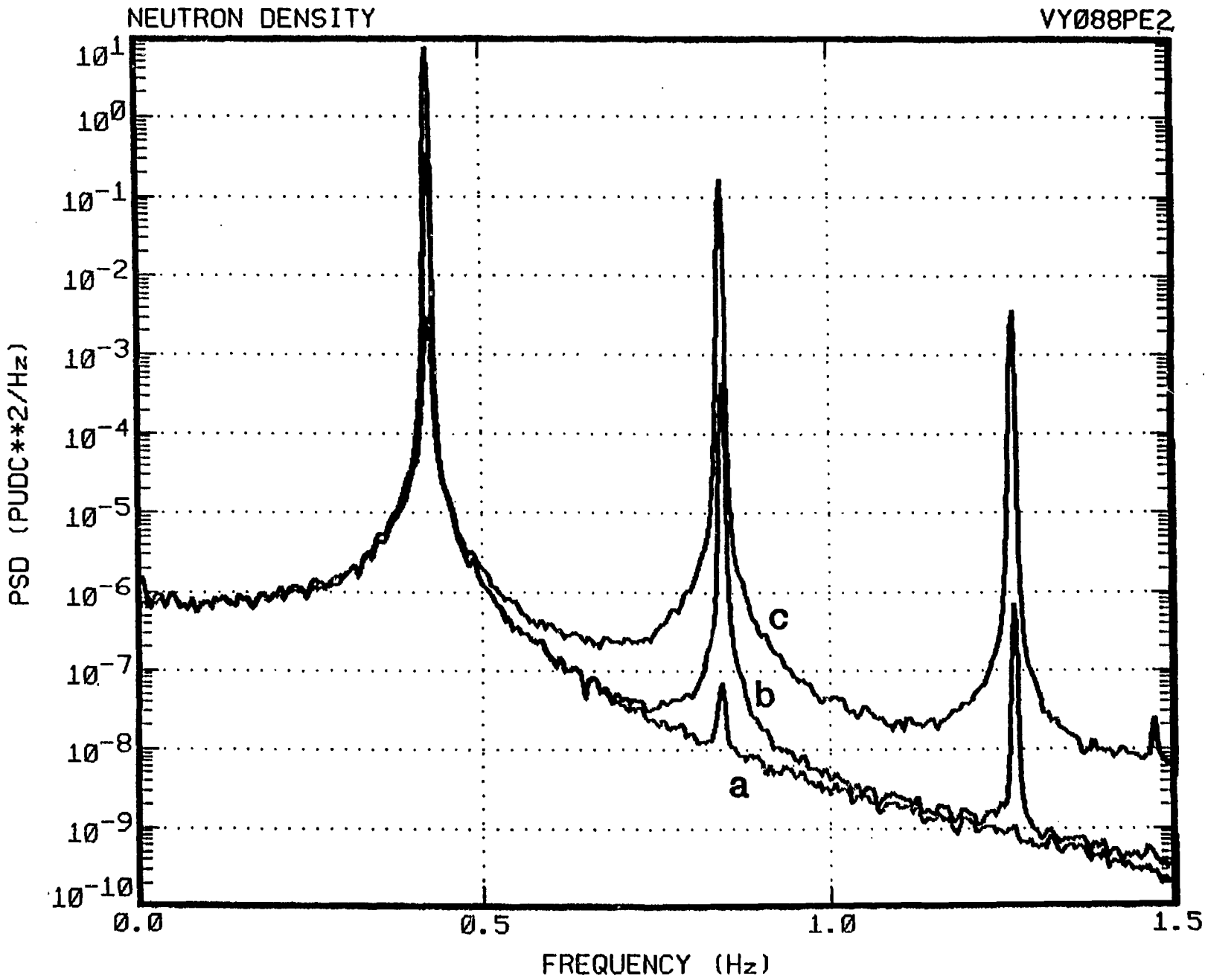
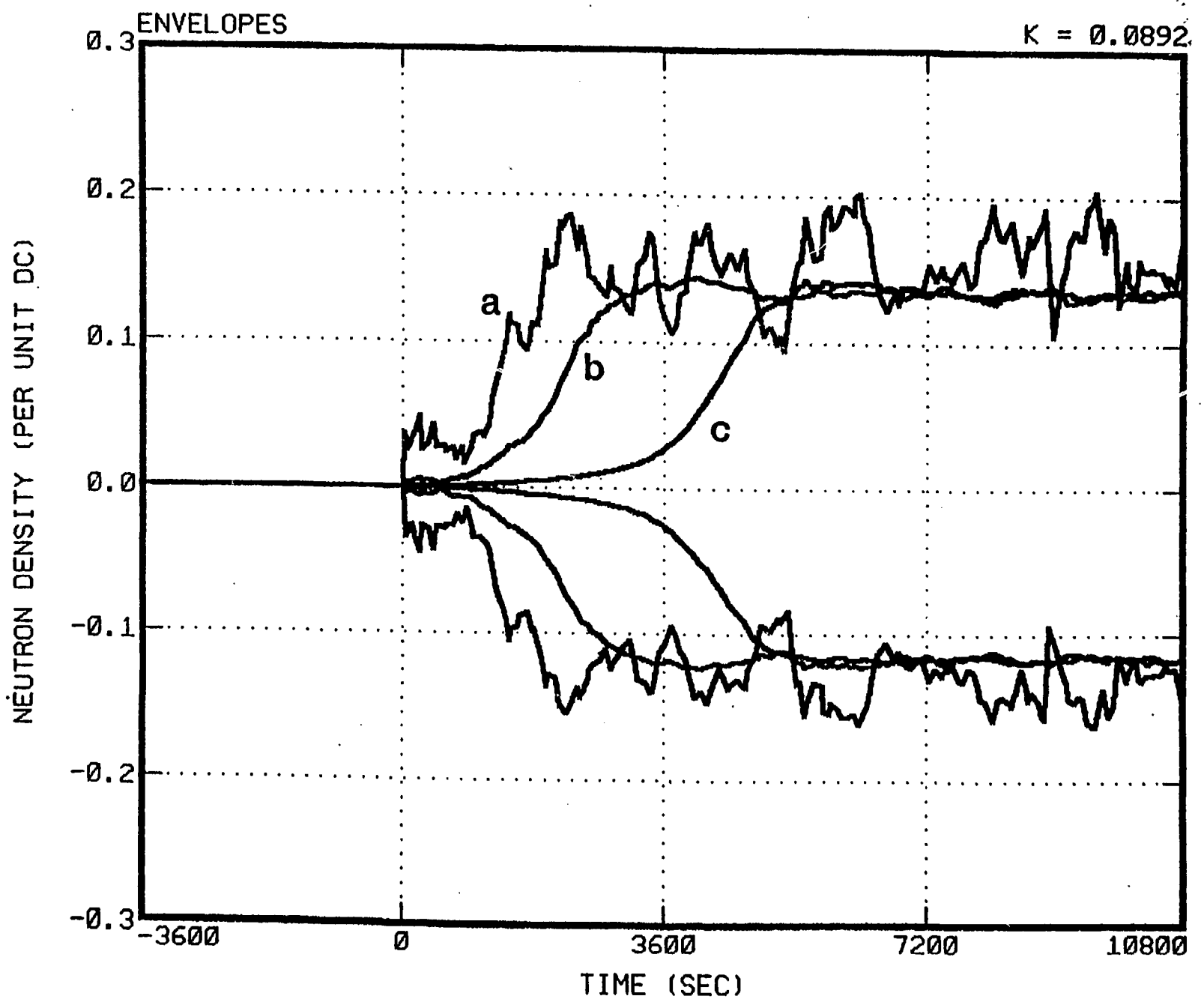

NEUTRON DENSITY
VY088PE2
PSD (PUDC**2/Hz)
FREQUENCY (Hz)
0.0
0.5
1.0
1.5
c
b
a

Fig. 2. Envelopes of the power oscillations for several values of the driving noise variance, σ^2, and K = 0.0892. Shown here is the appearance of a limit cycle whose amplitude is independent of the input, when a white noise source is applied at time zero: (a) $\sigma^2 = 10^{-5}$, (b) $\sigma^2 = 10^{-3}$, and (c) $\sigma^2 = 10^{-1}$, expressed in units of steady-state power.


ENVELOPES
K = 0.0892
0.3
0.2
0.1
0.0
-0.1
-0.2
-0.3
NEUTRON DENSITY (PER UNIT DC)
a
b
c
-3600
0
3600
7200
10800
TIME (SEC)