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A New Concept for Early Detection of BWR Instabilities

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INTRODUCTION

It is well established that there exist operational points for a BWR where unstable power/flow oscillations can be excited. The major concern is that these phenomena can result in violation of the Minimum Critical Power Ratio (MCPR) criterion, even at neutron power levels below the Scram Limit.

A great deal of research has been devoted to explain the physical mechanisms underlying these nuclear-coupled boiling instabilities (BWR instabilities). Researchers within the nuclear community have so far taken three different approaches to analytically investigate the problem: (i) classical frequency-domain stability analyses; (ii) large and detailed time-domain simulation codes; and (iii) bifurcation analyses. In any case, the major challenge is to make a trade-off between computational efficiency and accuracy of the stability predictions.

This paper outlines a novel approach to the analysis of BWR instabilities, providing a means for early detection of potentially damaging instabilities. In this approach, incipient power/flow oscillations are predicted by detecting small anomalies at an early stage.

The proposed anomaly detection methodology is built upon the fundamental principles of Symbolic Dynamics and Formal Languages [1, 2]. To the knowledge of the authors, this investigation is the first application of the theories of Symbolic Dynamics and Computational Dynamics in the safety analysis of a nuclear power plant.

DESCRIPTION OF THE WORK

In order to facilitate early detection of small changes in the BWR system parameters that may eventually lead to instabilities, it is proposed to excite the system with opportune *a priori* known stimuli and discover anomaly patterns, if any, from the resulting responses. The study considers BWR system operations in which anomalies do occur at a slow time-scale while the inferences are made based on the observation of the fast time-scale system dynamics. The algorithm of anomaly detection relies on this dual-time-scale analysis of the asymptotic response of the dynamical system.

The concept of the proposed methodology is schematically outlined in Fig. 1. Starting point is the generation of time series data using Thermal-Hydraulics/Neutronics coupled codes (namely TRAC-B/NEM and TRAC-M/PARCS [3,4,5]). The model of the BWR system is perturbed with an appropriate excitation stimulus to observe the asymptotic behavior at the fast time scale, making it possible to detect parametric or non-parametric changes in the BWR's dynamical behavior that may otherwise remain unperceivable over a long period of time.

The selection of the set of stimuli to be applied to the system is a critical step for the proposed methodology. The selected perturbation must not interfere with the normal operation of the plant (or, in this case, with the numerical simulation of the plant). In particular, unstable or excessive oscillations must not occur as a consequence of the input perturbations and the plant must return to the original state after the perturbation is terminated. On the other hand, the stimulus imposed to the system has to be ample enough in order for the analyst to infer the stability characteristic of the plant. These observations are especially true for externally applied small perturbations. Another possible approach consists in the analysis of naturally occurring self-sustained oscillations.

Next, a combination of Symbolic Dynamics and Formal Languages provides a tool for identification of small changes in the behavior of nonlinear dynamical systems.

The transition from the continuous dynamics to a discrete symbolic description is accomplished by choosing a suitable Poincare section for time discretization [1]. The resulting phase-space of the dynamical system is partitioned into a number of cells to generate a "coordinate grid". Each cell is labeled with a symbol and the set of all such symbols constitutes the "alphabet" of the symbolic dynamics. Such a mapping attributes a legal (physically admissible) symbol sequence to the system dynamics starting from the initial state, as the dynamic trajectory in the phase-space is represented by legal strings of symbols (symbolic language).

Computational Mechanics provides a probabilistic structure to the symbolic string, by means of a procedure known as epsilon-machine (ε-machine) reconstruction [2]. ε-machines belong to a special class of Deterministic Finite State Automata (DFSA) that can be used to quantify macroscopic or global properties. Examples are entropy rate and statistical complexity that reflect the characteristic average information processing capabilities of the system [6]. The construction procedure for ε-machines is based upon the translation of the string of symbols into a parse tree. A probabilistic structure is then added to each tree node in such a way that the transition probabilities between different system states (upon occurrence of each symbol of the alphabet) can be determined and represented by a (stochastic) connection matrix T, which is denoted as a vector representing any possible anomaly in the dynamical system. An appropriate norm of the difference between the matrices T under nominal and anomalous conditions is used in the investigation as a measure of anomaly.

RESULTS

In one of the author's previous work [7,8], the anomaly prediction algorithm has been validated on a rotorcraft gearbox for early detection of anomalies. The results derived from experimental data indicated that the language measure is at least as good as the sensor variance for detection of overload anomalies (which are detectable but not predictable) and is apparently capable of predicting damage anomalies before they occur.

The extension of the methodology to systems of bewildering complexity, such as BWR power plants, is currently in progress, with the time series data being generated. Applicability of the methodology and its physical significance in BWR instabilities will be demonstrated.

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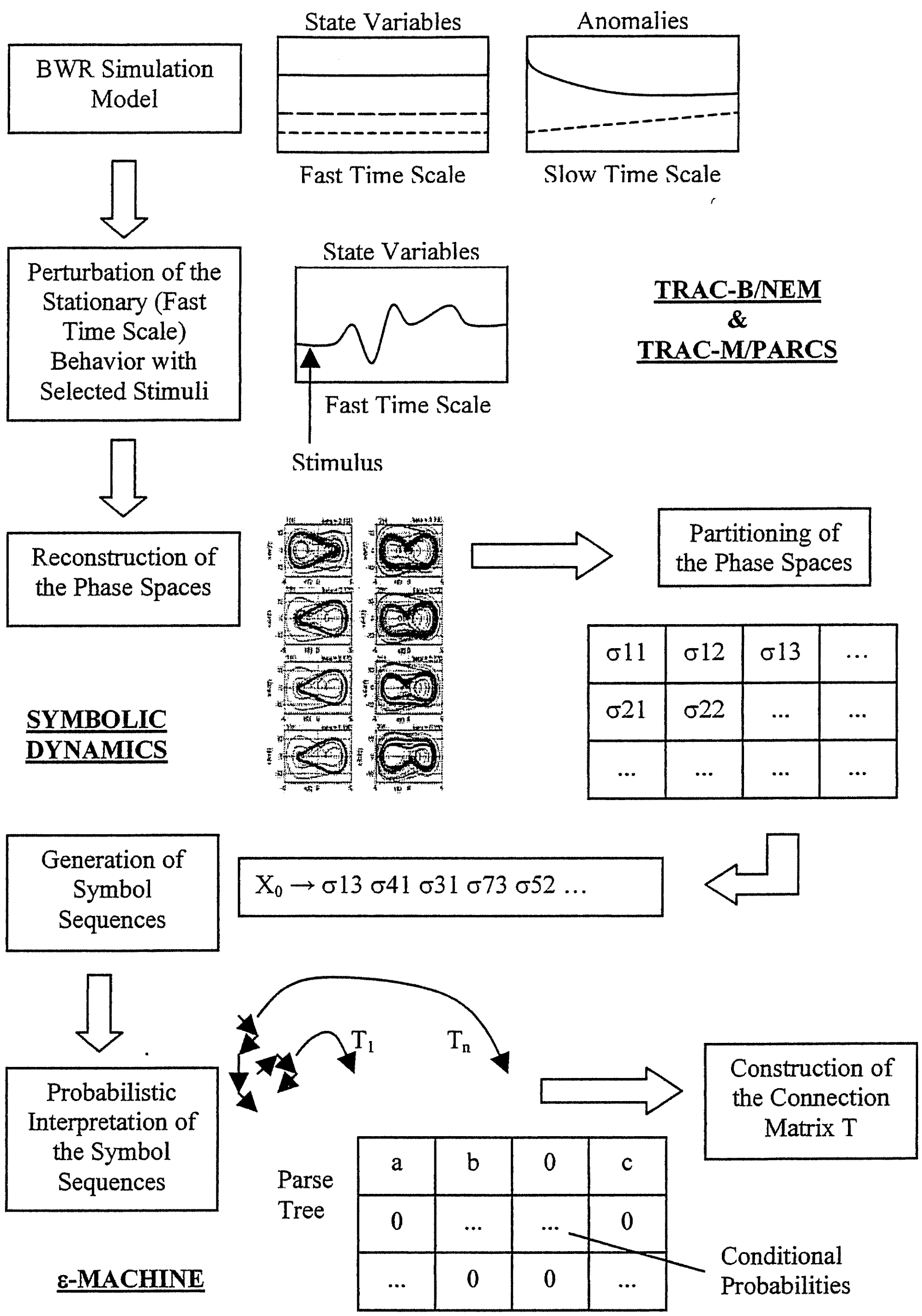

Fig.1. Concept of the Proposed Methodology