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Sensitivity analysis and dimension reduction of a steam generator model for clogging diagnosis

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ABSTRACT

Nuclear steam generators are subject to clogging of their internal parts which causes safety issues. Diagnosis methodologies are needed to optimize maintenance operations. Clogging alters the dynamic behaviour of steam generators and particularly the response of the wide range level (WRL – a pressure measurement) to power transients. A numerical model of this phenomenon has previously been developed. Its input variables describe the spatial distribution of clogging and its output is a discretization of the WRL dynamic response.

The objective of the present study is to characterize the information about the clogging state of a steam generator that can be inferred from the observation of its WRL response. A methodology based on several statistical techniques is implemented to answer that question. Principal component analysis reveals that clogging alters the WRL response mainly in two distinct ways. Accordingly, the output can be summarized into a vector of dimension 2. A sensitivity analysis is carried out to rank the input variables by magnitude of influence. It has shown that they can be divided into two groups corresponding to the two sides of the steam generator. Finally, sliced inverse regression is used to reduce the input dimension from 16 to 2. A sampling issue that arises when the input dimension is high is addressed.

The simplification of the original problem yields a diagnosis methodology based on response surface techniques.

1. Introduction

Pressurized light water nuclear power plants mainly consist of two separated water loops that exchange heat. The water from the primary loop goes first through the reactor where it is heated by the nuclear reaction and then through heat exchangers called steam generators (SGs) where it transfers heat to the water of the secondary loop. Steam exits the SGs by their upper opening and then flows through the turbines. A SG consists of a cylindrical tank (approx. 20 m high and 3 m wide) that contains the secondary steam–liquid mixture. The primary water enters the SG at its bottom and goes through a bundle of U shaped tubes. Eight circular plates called tube support plates (TSPs) maintain the tube bundle. The tubes fit in circular holes drilled in the TSPs. These holes are surrounded by additional quatrefoil holes to let the secondary steam-liquid mixture flow through. A SG diagram can be found in Fig. 1.

SGs internal elements foul with iron oxides carried by the secondary feed-water. This causes clogging of the quatrefoil holes that induces safety issues. Means to estimate TSP clogging are needed to optimize maintenance operations. The pressure difference measured between the steam dome and the bottom of the SG is called the wide range level (WRL). Previous studies [1,2] have shown that the shape of the WRL response curve to a power transient is altered by the clogging state of the TSPs and derived a diagnosis method that utilizing this link. The principle of the method is to compare measured response curves with simulations using with a mono-dimensional SG model. To assess the method's potential and make it reliable, it is necessary to characterise *how much information about the clogging state can be inferred from the WRL response*. This issue breaks down into three closely related questions:

- how does TSP clogging affect the shape of the WRL response?
- Are these effects different in nature and magnitude depending on the location inside the SG?
- What is the simplest formulation of input and output variables that captures these effects?

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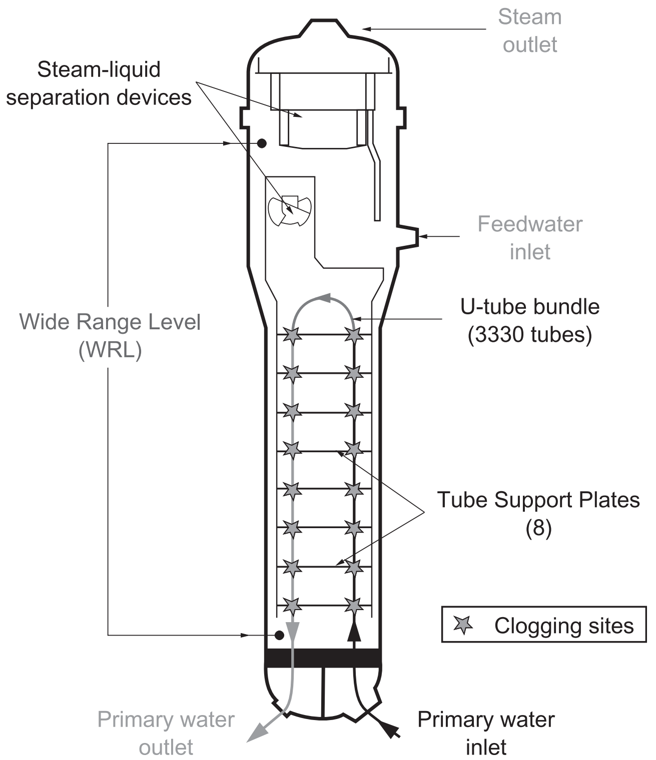

Fig. 1. Westinghouse type 51 steam generator.

The methodology presented here to answer these questions relies on computer intensive statistical methods. As the CPU time for a transient simulation with the 1D SG model is around 5 min, large samples of response curves corresponding to different clogging configurations can be generated.

Sensitivity analysis [3] and principal component analysis (PCA) [4] have been carried out to address the first two questions and the simplification of the output. The results suggested the use of a dimension reduction technique called sliced inverse regression (SIR) [5] to simplify the input. Along the process, bootstrap techniques were used to assess the robustness of the results and help with the interpretation. The SG numerical model and the statistical method that have been used are described in Section 2. The results are presented and discussed in Section 3.

2. Model and methods

2.1. Mono-dimensional steam generator model

The SG type examined here is the Westinghouse 51. EDF currently operates 48 of these, most of them being about 30 years old. A diagram representing the principal elements of a SG is given in Fig. 1. The SG model has been developed with the Modelica language using the Dymola software. Modelica is an object-oriented language especially designed for modelling physical systems [6,7]. It relies on a third party compiler and solver for simulation. Here, these roles were assumed by the Dymola software [8]. More specifically, Dymola version 6.0d and a solver named DASSL [9] have been used. It is capable of solving differential algebraic equations. The main elements of the model are as follows:

- primary fluid flow inside the U-tubes (single-phase flow);
- secondary fluid flow outside the U-tubes (two-phase flow);
- thermal transfer between the two fluids and through tube interfaces;
- two-phase singular pressure drops *e.g.* at the TSP quatrefoil holes;
- steam-liquid separation devices;
- feed water flow rate control system.

All these elements are mono-dimensional but the exchanger part is modelled as two channels: one for the *hot leg* (*i.e* concurrent exchanging side, where the primary fluid enters the SG) and one for the *cold leg* (*i.e* countercurrent exchanging side, where the primary fluid exits the SG). The exchanging channels are composed of 20 evenly spaced meshes. The choice of mono-dimensionality and of the number of meshes is driven by the applications for which the model has been developed. On the one hand, it must be able to simulate the dynamic response of a SG precisely enough so that information about clogging spatial distribution is not lost by averaging processes. On the other hand, computation time for simulation must be kept low so that computer intensive methods can be used. Typical Monte Carlo methods require hundreds if not thousands of model runs. For instance, the method of Sobol' for sensitivity analysis can often require an order of magnitude of 10^3 simulations per input variable to converge [3]. The number of simulations needed to obtain robust results with SIR is dependent on the model complexity. In the present case, the results were still fluctuating when increasing the sample size from 3×10^3 to 5×10^3 while they were stable for a sample size of 10^4. In order to be able to use such methods with a reasonable computation time, the computation time had to be under approximately 10 min using regular workstations. Additional details about the model can be found in Ninet and Favennec [2].

2.1.1. Model output definition

A power transient is simulated by varying the model boundary conditions. The transient used in the clogging diagnosis method is a roughly linear power decrease from nominal power to 40% of nominal power in an average time of 1148 s. It is modelled by a linear variation of primary inlet enthalpy and secondary outlet steam flow rate. The feed water flow rate is being determined by the control system. The model output is a vector, **w**, of dimension 1148. Its coordinates are the values of the WRL at each 1 s time step.

2.1.2. Model input definition

There are eight TSPs in the SGs under study and two 1D channels so the vector describing the clogging state, **x**, is of dimension 16. Each of its coordinates is a *clogging ratio* associated to a half-TSP. Clogging ratios are defined as the ratio of the blocked area to the total area of the holes without clogging:

$$x_i = \frac{(\text{clogged area of half}-\text{TSP})_i}{(\text{total holes area of half}-\text{TSP})_i}. \tag{1}$$

Clogging affects the WRL response by increasing the singular pressure drop at TSP crossings. In the model, the corresponding pressure drop coefficients depend on the clogging ratios through a function derived from experiments conducted on a 1:4 scale mock-up of TSPs and tubes [10].

2.1.3. Preliminary analysis

The singular pressure drop at a TSP crossing increases with the clogging ratio and steam fraction and decreases with the pressure of the steam–liquid mixture. The pressure is nearly the same in the two legs and it decreases as the secondary mixture rises inside the SG. The steam fraction equals zero at the bottom of the SG (liquid alone) and increases as the fluid rises and gets heated by the tubes. Its increase is sharper on the hot leg. From this,