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Neural networks for displacement analysis in an advanced gas cooled reactor core model

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ABSTRACT

This paper presents a Neural Network (NN) approach for displacement analysis with applications in modelling the seismic response of the UK's Advanced Gas Cooled Reactors (AGRs). A quarter sized physical model of a reactor core was developed at the University of Bristol to provide experimental validation to the existing numerical models that support the seismic resilience assessments of the AGRs. The physical model outputs include displacement and acceleration datasets of considerable size and complexity, collected for a range of seismic inputs and postulated component damage scenarios. Rich sets of displacement data were employed in training two NN models that can predict displacement at user-defined locations in the core physical model and can map the correlation between the component relative displacements. Understanding component displacements is particularly important, as such displacements may affect the channel shapes and can cause local and general distortion of the core. This paper presents the development, testing and performance of the NN models. The NNs yield predictions that compare well with the experimentally obtained parameters. As more experimental test data become available, the NN's prediction capability will benefit from accumulated training. In the future, the NNs will be incorporated into a multi-layered framework for dynamic response prediction and analysis.

1. Introduction

The aim of this paper is to test the validity of use of NNs as predictor tools for a complex multi-rigid body dynamics problem. Neural networks (NNs) are widely used in all areas of engineering and experimental research to model systems with numerous variables and complex non-linear response, and their role could be of pattern recognition, object classification or prediction (Beale and Jackson, 1990). NNs act as nonlinear modelling systems that consist of processing units or neurons interconnected by means of weights. The model is represented by the values of these weights, which are established during network training. How the strengths of the neuron connections are obtained during the training phase to achieve a desired overall behaviour of the network is governed by the training algorithm (Beale and Jackson, 1990, Beale et al., 2016). Each neuron has an associated transfer function that relates its inputs to its output. Given a set of inputs, a NN can predict the outputs without the need for *a priori* assumptions with regards to the relationship between the inputs and the outputs. The different types of NN architecture, transfer functions and training algorithms in use today form a vast area of mathematical research (see, for example, Beale and Jackson, 1990, Heaton, 2012; Hagan et al., 2014).

In the nuclear industry, a plethora of computer systems based on object classification NNs have been proposed as diagnostic tools for the direct mapping of plant signals into components faults (see for example Uhrig, 1991a,b, Bourguet and Antsaklis, 1994, Santosh et al., 2007). NNs have also been applied for the characterization of normal operating plant conditions and transient data pre-processing, and have been used in combination with other computer tools in hierarchical multi-level diagnostic systems (Cheon and Chang, 1993; Ohga and Seki, 1993; Bartal et al., 1995; Santosh et al., 2007). Several NN-based systems have been proposed to deal with off-line nuclear power plant – related issues, such as fuel reload optimization, power and heat distribution in the fuel elements, fault detection in fuel elements or steam header welds (Reifman et al., 1994, Reifman et al., 1996). Other more recent projects discuss the feasibility of using neural networks for modelling the plant thermodynamics and for the analysis of plant vibrations (Westwick, 2007). In the UK, a novel approach to generate models of systems for real time monitoring in the nuclear industry has been

Abbreviations: AGR, Advanced Gas-cooled Reactor; IR, Infrared; MLA, Multi Layer Array; MSE, Mean Squared Error; NN, Neural Network; NNC, National Nuclear Corporation; RRS, Required Response Spectrum; SD, Standard Deviation; UOB, University of Bristol

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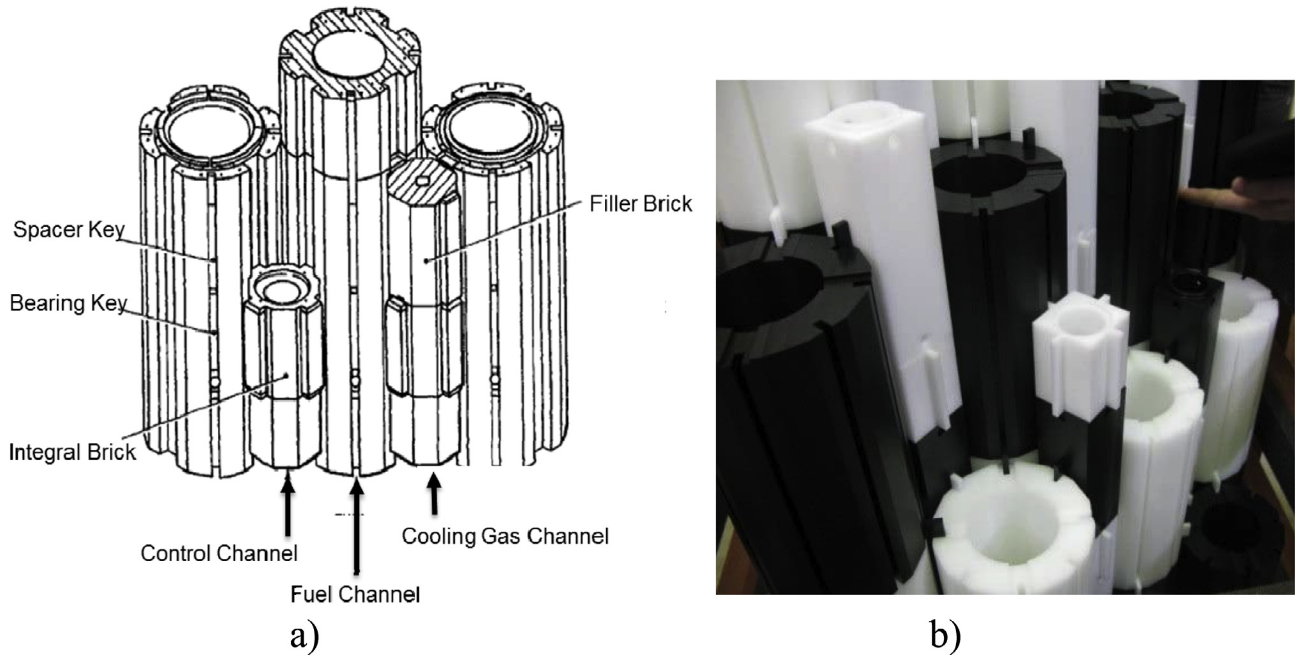

Fig. 1. Arrangement of AGR core components (a) and MLA model components made of acetal (b).

developed using tools based on binary neural networks and associative memory techniques (Cybula, 2016). The most widely used type of neural network, both for nuclear plant diagnostics and plant model identification, is the feedforward back propagation NN which consists of a layered arrangement of neurons. The information flows unidirectionally from the input layer of neurons to the output layer, while the error between the NN prediction and the values of the training set propagates backward through the network. This type of NN has been classified as an universal approximator (Hornik et al., 1989).

This paper presents the use of the NN approach in the context of physical modelling of an Advanced Gas Cooled Reactor (AGR) core. The AGRs are the second generation of British gas-cooled nuclear reactors, using graphite as the neutron moderator and carbon dioxide as the coolant. In the United Kingdom, there are seven AGR power stations, each with two identical reactors. Their cores comprise of a stacked array of hollow, prismatic graphite bricks and interlocking keys and are designed to fulfil three fundamental functions: provide neutron moderation, allow movement of fuel and control rods and allow gas flow for cooling. These functions must be maintained in normal operating conditions, but also during hazardous natural events, such as earthquakes. According to current international standards, a nuclear plant should be qualified against at least 0.1 g peak ground acceleration, while the plant operators require that their AGRs can be safely shut down and held down in the case of a more severe seismic event with a probability of exceedance of 10^{-4} per annum. The seismic capability of the AGRs is subject to continual examination by the operators as part of a strategy that involves the development of enhanced analytical methods and physical models for static and dynamic behaviour (Neighbour, 2007; Neighbour, 2013; Flewitt and Wickham, 2015). The earliest physical model for seismic behaviour included a simple 9 × 9 brick array, employed by the National Nuclear Corporation (NNC) in 1985. Later on between 2008 and 2012 a single layer 20-rings array model and a 4 × 4 × 8 array ('the minicore') were developed by the University of Bristol (UOB) to explore the basic mechanics of the core system and prepare the ground for a more sophisticated modelling tool (Dihoru et al., 2016).

In 2014, a quarter scale 8-layer-20-bricks-across AGR core model ("the Multi Layer Array (MLA) rig") was commissioned at the UOB for the investigation of the seismic behaviour of these complex systems. The rig can generate brick displacements of sufficient magnitude to exceed current seismic assessment limits when simulating the effects of postulated component degradation (i.e. cracked bricks and/or failed keys) and increased brick-to-brick clearances arising from radiation shrinkage in the AGR cores. The MLA was tested on the earthquake simulator ('shaking table') at UOB. It provided useful insights into the dynamics of core arrays and feeds large amount of data into the existing numerical models (Kralj et al., 2005, Koziara and Bićanić, 2011) for validation.

Nine MLA experimental configurations comprising ~42,000 components and ~3200 measurement sensors generated ~7 Tb of data. The physical model outputs include displacement and acceleration datasets of considerable size and complexity that feature all the challenges associated with 'big data' capture, storage, transfer, analysis, visualization, updating and information privacy. The vast amount of data that resulted from the tests are challenging in both handling and interpretation and require bespoke software for structuring and analysis. Besides the more conventional processing tools, a new neural network (NN) approach has been developed to predict the displacement of bricks in the top layer of the array, based on past response history. Such predictions are important in understanding the expected response for a user-defined seismic input and for recognizing the correlations between the individual component displacements at various locations in the array. Such displacements may reflect the local and the general core distortion, as well as being an indicator of the behaviour of the top of the control and fuel channels. The NN models and the details of NN training and testing are presented together with the NN simulation results. The NN's prediction performance shows that the new models are efficient in dealing with highly non-linear, time-dependant displacement data and that they are capable of recognizing patterns of behaviour determined by both geometry and dynamic input.

2. MLA experimental rig

The MLA consists of an 8-layer assembly of quarter scale model bricks and model keys made of a rigid engineering plastic (acetal). All of the AGR graphite component types are represented in the MLA, i.e. fuel (lattice) bricks, interstitial bricks, filler bricks, filler, spacer and loose bearing keys (Fig. 1). The multi-layered array of components is