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Fault detection of nuclear reactors by estimation of unknown input for systems with disturbances

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HIGHLIGHTS

- A framework for estimation of friction force during refueling of nuclear reactor is presented.
- An unknown input Kalman filter is introduced for reducing the uncertainty associated with the data.
- The estimation technique is used to estimate the friction force during fault detection of the graphite core of Advanced Gas Reactor.

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ABSTRACT

Some traditional methods for parameter estimation and fault detection may lead to poor results with nuclear systems in practice because approximations and uncertainties in the system models possibly result in unexpected plant unavailability. This experience has led to an interest in development of estimation and fault detection methods for nuclear systems. In this paper, we present a framework for estimation of friction force during refueling. Specifically, an unknown input Kalman filter is introduced for reducing the uncertainty associated with the data, that arise due to many reasons including random noise and disturbances. Based on our proposed model, the estimation technique developed by this paper is used to estimate the friction force during condition monitoring of the graphite core of Advanced Gas Reactor.

1. Introduction

In order to meet the increasing energy needs in the world, current and future widespread usage of nuclear reactors depend mostly on the safe and cost effective utilization of nuclear systems and operational strategies. Developing diagnostic methodologies have become increasingly significant for nuclear power plants in order to provide smooth and uninterrupted plant operation in the face of varying power demand (Ablay and Aldemir, 2013). Estimation methods play an important role in the nuclear industry since there are many unmeasurable states and parameters in complex nuclear systems. They are used to estimate state variables and parameters for the aim of online condition monitoring, critical parameter estimation (Qaiser et al., 2009).

The state estimation problem for unknown inputs deterministic systems is being increasingly discussed in both research and applications. Many researchers have investigated the effect of perturbations on standard estimation procedures. In the field of state estimation in presence of unknown inputs, a large number of investigators have focused their attention on building full-order or reduced-order observers for deterministic systems (Hou and Müller, 1992). The approach of modeling the unknown inputs by the response of a suitably chosen dynamical system increases the dimension of the observer considerably. More interesting other approaches are developed by Wang et al. (1975), Yang and Wilde (1988), and Guan and Saif (1991). However, few approaches have been developed for unknown inputs stochastic systems. Most of these approaches assumed that all system parameters, noise covariance's and inputs are known. In practice, there are many situations in which this assumption is not true. Most importantly, the standard Kalman filtering technique may fail in the presence of parametric uncertainties, noise covariance uncertainties or unmeasurable inputs. The problem of designing an observer for a linear system partially driven by unknown inputs has been studied widely for example: Bejarano et al. (2009), Gillijns and De Moor (2007) and Floquet and Barbot (2006). Such observers can be important for systems subject to disturbances or with inaccessible inputs, or when dealing with the problem of fault diagnosis.

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It has to point out that a discrete-time estimator can be used for discrete-time system but also for systems under sampling. In that case, the order of approximation is an important question and some time derivatives of the unknown inputs may appear (Kang, 2006). For all these reasons, the design of discrete-time estimator is more and more popular and can be more appropriate when dealing with real applications especially in signal processing and condition monitoring, for example Yang et al. (2006).

In nuclear power plants, the most commonly used methods are signal analysis and multivariable statistical analysis based approaches (Ma and Jiang, 2011). Signal analysis based methods are used when the process signals include periodic or stochastic fluctuations. A large amount of data must be stored to generate a model for fault detection. The signal and statistical analysis based methods can be applied offline and online fault detection. Model-based methods use mathematical models of processes to compare measurements of the process to that estimated by the model. They are usually the most cost effective methods since they do not require additional hardware or physical instrumentation in the plant (Hwang et al., 2010). The most critical plant equipment are instrumented well enough to develop and deploy such modeling techniques. The models can be based on physical modeling or empirical modeling. The strength of the physical modeling for condition monitoring is the ability to calculate the as-built reference plant behavior without failures, and real-time fault diagnosis. In addition, physical models have the advantage for systems that are new and have no prior operational data. The main weakness of physical modeling is that the model should be accurate, and it can be too costly and time consuming to compile for large-scale systems.

In this paper the developed estimation methods are applied to estimate the condition of the graphite core of Advanced Gas Reactor (AGR) based nuclear reactors (Pang et al., 2007). Model-based fault diagnosis approaches are generated by building a fuel assembly moving model firstly. Since changes of the wall friction in the fuel channels reflect the geometry of reactor core, an unknown-input Kalman filtering technique has been developed for the purpose of dampening the sensor noise and disturbances that are not related to friction force. The idea is originally to employ the unknown-input Kalman filtering technique to the fuel grab load trace data as a data-preprocessing algorithm, prior to further analysis of the fuel grab load trace data. In addition, it is found that the unknow-input Kalman filtering algorithm also could be exploited in order to gain a deeper understanding of the condition of the reactor core and to quickly identify significant distortions (brick cracks) in the fuel channels.

The paper is organized as follows. In Section 2, the condition monitoring problem of the advanced gas-cooled nuclear reactor core is presented. In Section 3, the model of a linear system with unknown input is addressed. In Section 4, we give the main results on the estimation of unknown input. The simulation results are given in Section 5. Finally, Section 6 concludes this paper and highlights future work directions.

2. Fault detection of nuclear reactors

The biggest challenge of advanced gas-cooled reactor nuclear is that it is impossible to repair or replace the graphite brick, hence the graphite core is one of the crucial components that determinate the operational life of a nuclear station. The reactor core is composed of hundreds of hollow graphite bricks. The graphite ages because of neutron irradiation and radiolytic oxidation that will cause distortion and potentially cracks of the bricks. The ability to measure or estimate the condition of the graphite core in Fig. 1 of nuclear reactors is a significant strategic importance for operators of nuclear power plants in the near future, particularly for those that aim to seek licenses for nuclear power plant lifetime extensions. Unfortunately, the direct measurement of the core condition is costly, time-consuming and very difficult. For this reason it is desired to develop alternative methods that can provide the necessary information about the core condition without direct measurements. This motivates the research of fuel grab load trace (FGLT) data to provide additional information relating to the current condition of the core. Cracks can represent the extremes of graphite brick distortions. These cracks in the graphite core result in a step-change in the friction and hence load across a brick layer. It is expeced that the friction changes can be found through analysis of FGLT.

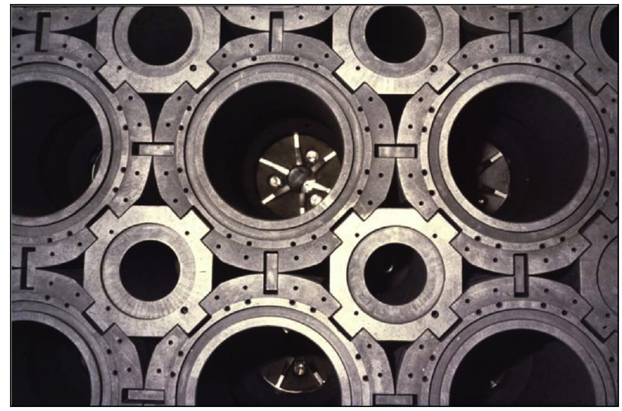

Fig. 1. A picture of graphite cores of an Advanced Gas Reactor (AGR) (Steer, 2005).

The fuel assembly usually has two sets of brushes which guide it through the reactor during refueling. These brushes form an interface with the channel wall and changes in channel diameters are reflected in the FLGT data. Sensors of load cells on the refueling machine directly measure the apparent load of the fuel assembly, as it is being lowered into, and raised out, of the reactor core. The measurement load data are made up several parts, the most important ones are: the weight (mass) of the fuel assembly, the frictional forces and the circulated gas.

The weight of the fuel assembly depends on its mass, which changes during the reactor's operation. During the extraction process it is unknown, however it can be determined once the fuel assembly is out of the reactor from the grab load trace data.

The friction forces are caused by the interaction between the stabilizing brushes on the fuel assembly and the channel wall. The magnitude of the friction component will directly depend on the channel wall geometry, which means that any distortion in the channel geometry will be reflected in the friction force. The sign of the friction component depends upon the direction of travel of the fuel assembly. During the reactor discharge, removal of the old fuel assembly from the core, friction opposes the movement of the assembly and therefore a narrowing of the channel will result in an increase in the apparent load of the fuel assembly (i.e. friction force is negative). During the reactor charge, new fuel insertion, the friction force supports the weight of the fuel assembly resulting in a decrease in the apparent load from a narrowing of the fuel channel (i.e. friction force is positive).

Finally, the circulated gas produces a buoyancy force that makes the fuel assembly to appear lighter. The buoyancy force is defined with sign convention that an up thrust is positive because in both cases, reactor charge or discharge, has the same effect. The sign convention for brush friction depends on refueling operating being represented.