Condition Monitoring for a Nuclear Fusion Cryogenic Vacuum System

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***Abstract*—Neutral beam heating devices are an important support system for many magnetic confinement nuclear fusion experiments. An ongoing activity of Joint European Torus experiment is to increase the availability of neutral beam heating devices. Cryogenic vacuum systems are an important subsystem of these devices. In order to reduce experimental time lost to unplanned maintenance, investigation and avoidable failures, a condition monitoring scheme targeted on a cryopumping vacuum system is proposed. This paper presents the design and design methodology of a condition monitoring scheme for the neutral beam heating cryogenic vacuum systems at the Joint European Torus.**

***Index Terms*—Condition Monitoring, Cryogenics, Fault Detection and Isolation, Neutral Beam Heating, Nuclear Fusion, Vacuum Systems**

I. Introduction

MAGNETIC confinement nuclear fusion devices all require a vacuum to be maintened within the reaction vessel. In experiments utilising neutral beam heating, such as the Joint European Torus (JET), a vacuum also has to be maintained in the neutral beam heating vessel (NIB). Any fault or event that results in this vacuum being compromised will prevent the fusion device from operating.

At the Culham Centre for Fusion Energy (CCFE), the organisation operating JET, improving the availability of the availability of the experiment is an ongoing activity. Remote robotic handling, extreme ranges of temperatures and pressures, ionising radiation, high energy neutron bombardment and the complexity of the systems involved all contribute to a challenging maintenance environment.

Traditionally when faults have occurred, CCFE staff have engaged in manual diagnostic procedures, examining a large amount of process data "by hand" to isolate faults. However, this is a time consuming exercise which relies heavily on the experience of the engineering staff. In order to reduce the workload on engineering staff, and to reduce time spent diagnosing and isolating faults, there is a push towards developing automatic fault detection and isolation (FDI). This provides the motivation for the research presented here, with the neutral beam injector systems as a target for a case study.

The design of neutral beam injector systems is discussed by G Duesing[1], and more recently, Ciric[2] and Ciric et al[3] wrote about new developments in JET's NIB cryopumping scheme. An initial case study conducted by Khella et al.[4] emphasises the importance of the cryogenic vacuum system in neutral beam heating, and highlights it as a possible target for a condition monitoring scheme. Wright[5], presents a non-linear simulation model of the JET cryogenic vacuum system, on which the condition monitoring scheme described here is to be deployed. The design and design methodology for the condition monitoring scheme is presented in the following section.

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II. Design Methodology

Fig. 1 is an illustration of the cryogenic vacuum system. Liquid helium is delivered from the helium tank through a transmission line to the heat exchanger, onto which trace gases condense. Gaseous helium evolved from the heat exchanger is fed back through a different transmission line to a helium liquefier, or disposal baloons.

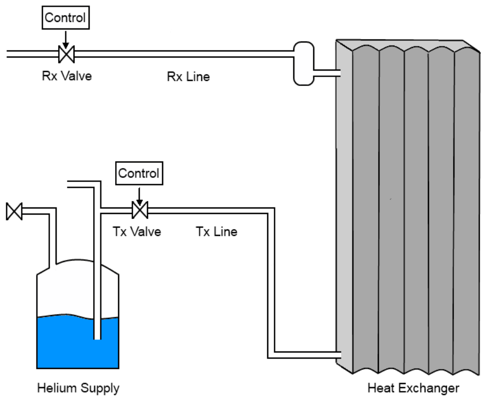

Fig. 1. An illustration of the cryogenic vacuum system

Fig. 2 is a schematic of the condition monitoring scheme. A series of explicit numerical models are used to predict the expected behaviour of the plant. This prediction is checked for consistency against physical measurements taken from the plant. Differences can be indicative of an abnormal condition or fault.

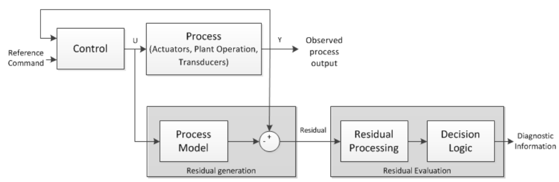

Fig. 2. Schematic of the condition monitoring scheme

Fig. 3 is an illustration of the methodology used to design the condition monitoring scheme.

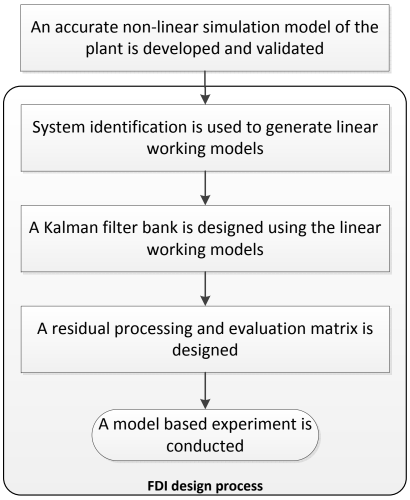

Fig. 3. An illustration of the methodology

A. Generation of Linear Working Models via System Identification

The non-linear simulation model presented in [5] was used to generate data sets for use in a system identification process. A series of linear single-input single-output (SISO) state space working models were generated relating each output to each input. The process variables are listed in tables I and II.

Process variable (Inputs)	Unit
Supply & return valve position	%
Helium supply temperature	K
Helium tank pressure	BarA
Valve box return pressure	BarA

TABLE I
LIST OF MEASURED PROCESS VARIABLES

Process variable (Outputs)	Unit
Phase separator level	%
Supply & return line pressure	BarA and BarG
Capillary delta pressure	mBar
Top and bottom wall temperatures	K
Helium return temperature	K
Helium tank fill level	%
Helium tank fill volume	l

TABLE II
LIST OF MEASURED PROCESS VARIABLES

The data sets were used to estimate the parameters of several sets of discrete time ARX-models (auto-regression with exogenous variables), using least squares. One ARX model was selected per set. The objective of this procedure was to select a single linear model for each input-output pair, with a trade off between model order (complexity) and accuracy, in the well known state space format.

B. Kalman Filter Design

One linear discrete time Kalman filter was designed for each of the the ARX-models, and put into a bank structure. One filter was designed for each input-output pair (see tables I and II). Information about historical measurement (sensor) noise and anticipated process noise (or modeling error) was used to select the noise covariance matrices.

C. Residual Evaluation

In order to provide diagnostic information, the residuals generated by the Kalman filter bank are processed by a residual evaluator. For this application, a simple thresholding, low-pass filter and voting arrangement was designed to identify and isolate residuals indicative of faults. Thresholds were set for each residual, so that each residual signal could be mapped onto a binary variable. A range of faults was simulated, and the combination of these binary variables was used to isolate each fault. It should be noted that each combination may map onto more than one fault.

D. Model Based Experiment

The non-linear simulation model was adapted to simulate the effect of several different faults. The output of this modified simulation model was used to drive the condition monitoring scheme. A paper describing the results of this experiment is currently under review, having been submitted to *Fusion Engineering and Design*.

III. Conclusion

A design methodology for a condition monitoring scheme for a fusion vacuum system has been presented. Using a numerical model based approach works well for fusion applications, because of the availability of a large amount of process data and detailed design information. Model based experiments are also well suited to fusion applications, because of the limited time available for physical experimentation. The confidence given by the success of a scheme in simulation allows more effective use of physical test platforms.

Future work will involve commissioning the condition monitoring scheme on the Neutral Beam Injector Test Bed facility run by CCFE. This work is currently being planned.

References

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