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A fuzzy-based gas turbine fault detection and identification system for full and part-load performance deterioration

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ABSTRACT

Considering the fact that the signs of performance deterioration in the main components of gas turbines vary in different operating points, thus designing a Fault Detection and Identification (FDI) system using a single fault pattern for all engine operating ranges can reduce the ability of the diagnosis system to identify the intensity or even the type of any potential degradation. So, in this article, with the aid of the "load" parameter as an augmented input and using the fault patterns obtained at different part-load conditions, a fuzzy-based FDI system is proposed for an industrial two-shaft gas turbine with the ability to use in both the full and part-load operations. In the proposed FDI system, fuzzy rule base is generated by a table look-up scheme and by employing the available input/output data extracted from fault signature table. Moreover, a global optimization technique is used to determine some database parameters, such as the number of membership functions of input variables and their standard deviations. The optimization is carried out to make a compromise between the diagnosis accuracy and robustness against measurement noise. In the present work, the performance of the proposed FDI system is evaluated against the most common cause of gas turbine performance deterioration i.e. fouling and erosion in terms of the success rate and the estimation accuracy at different levels of sensor noise. The results obtained indicate that the proposed FDI system can considerably reduce the average estimation error by 0.1–0.75% and increase the success rate by 10–20% compared with the diagnosis systems designed for a specific operating point. The results also demonstrate that the proposed FDI system has robust performance against measurement uncertainties, and moreover smearing effects are rarely seen in the results.

1. Introduction

Gas turbines are always exposed to damages and their performance may be deteriorated over time, due to many reasons such as fouling, corrosion, erosion, blade tip and seal clearance, thermal distortion, foreign (or domestic) object damage, and also the fuel nozzle clogging. The consequences of this performance deterioration can vary from an increase in fuel consumption, a decrease in components efficiency and lifetime to instability and the complete destruction of the gas turbine. Hence, increasing the efficiency and the useful life of the engine components on the one hand and maintaining the system stability on the other hand are considered among the main motivations for designing a Fault Detection and Identification (FDI) systems.

In the most general manner, the fault detection techniques in gas turbines are classified into two categories: The "non-performance-based" methods and "performance-based" methods [1]. The fault detection methods like *visual inspection*, *vibration analysis*, and *oil analysis* can be considered as the non-performance-based methods, and the methods in which the diagnosis procedure are performed by using a set of measured parameters to obtain the engine health parameters deviations can be considered as the performance-based approaches.

The performance-based gas turbine diagnosis which is also called Gas Path Analysis (GPA) has been developing considerably so far, in terms of diversity and capability. Among the presented performance-based gas turbine diagnosis methods, the techniques based on Influence Coefficient Matrix (ICM) inversion [2], Weighted Least Square (WLS) [3–5], Kalman-Filter (KF) [6], Bayesian-belief network [7], the Artificial Neural Network (ANN) [8–10] and also the methods based on global optimization [11–13] can be mentioned as the most common performance-based FDI techniques.

The FDI techniques based on KF and WLS are quick and require limited computational effort due to their recursive nature. Moreover, unlike the diagnosis method based on ICM inversion, both

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Nomenclature

Symbols

FDI	Fault detection and identification
CF	Compressor fouling
CE	Compressor erosion
T1F	Gas generator turbine fouling
T1E	Gas generator turbine erosion
T2F	Power turbine fouling
T2E	Power turbine erosion
I/O	Input/Output
SF	Scaling factor
FMF	Fuel mass flow
NGG	Gas generator rotational speed
NPT	Power turbine rotational speed
EGT	Exhaust Gas Temperature
NL	Noise level
TSK	Takagi–Sugeno–Kang
DB	Data base
RB	Rule base
IWO	Invasive weed optimization
PSO	Particle swarm optimization
MF	Membership function
FST	Fault Signature Table
X	Health parameter
Y	Compressor/turbine's map parameter
T	Temperature
P	Pressure
z	Measurement parameters
x	Input parameters of a fuzzy system
y	Output parameters of a fuzzy system
$\bar{y}$, c	Constant parameters of the consequent part of each fuzzy rule
A	Membership functions of the antecedent part of each fuzzy rule
m	Number of measurements
n	Number of health parameters
M	Number of rules
NMF	Number of membership functions
D	Firing degree of a rule
f	Fuzzy function
J	Objective value
w	Weighting factor
$norm$	Normalization factor
$\bar{Er}$	Average estimation error
SRI	Success rate index
$\Delta\hat{x}$	Estimated health parameters deviation
Δx_{act}	Actual health parameters deviation
N_T	The total number of I/O pairs in the data base (w + w/o noise)
Tol	Tolerance

Greek

Γ	Flow capacity
η	Isentropic efficiency
δ	Dimensionless pressure
θ	Dimensionless temperature
σ	Standard deviation
μ	Membership value

Subscript

des	Design point
cl	Clean condition
det	Deteriorated condition
Map	Reference map
C	Compressor
T	Turbine
X, x	Health parameter
amb	Ambient
cor	Corrected
Obs	Observed
n	Noisy measurements
k	Number of noisy measurement deviation generated for each noise-free I/O pair
imp	Implanted
$detec$	Detected

Superscript

i	Measurement's counter (rule counter)
j	Individual's counter
a, b	Constant coefficients
N^*	Predefined measurement noise
NT	Considered measurement noise for generating noisy I/O pairs

the KF and WLS-based FDI methods can deal with the measurement uncertainties. But some studies [12,14–16] have claimed that the results of these methods may be affected by the smearing effects [17,18] (attributing a fault to a clean component).

The ability to deal with the measurement uncertainties and high computational speed are the main advantages of the ANN-based FDI systems which attracted a lot of attention in the last decades. But, since the ANN systems are often trained in a black-box fashion, the performance of these diagnosis systems may be somewhat declined when dealing with untrained data.

The Global Optimization-based FDI (GOFDI) systems have the ability to expose the measurement uncertainties and, most importantly, have the capability to deal with the deteriorations that their signatures are not extracted before. However, these advantages of the GOFDI systems are at the expense of far more computational cost than the pattern recognition-based FDI systems (like Fuzzy-based and ANN-based diagnosis). Thus, the (existing) GOFDI systems may not be appropriate for detecting sudden faults in gas turbines. However, the authors believe that the GOFDI method has a very bright future ahead by employing innovative global optimization techniques accompanied by the increasing progress in computer processors.

Nowadays, the FDI methods based on the fuzzy logic has attracted a lot of attention due to their fast response, ease of implementation and high accuracy and reliability. The nonlinear nature of the fuzzy systems and their robust performance against the measurements uncertainty has made these systems an effective tool for gas turbine fault diagnosis. Furthermore, unlike the FDI systems based on the ANN (which are usually considered as black-box estimators), the fuzzy-based FDI techniques are known as universal approximators due to their intuitive and discursive governing rules.

Moreover, it should be added that, unlike the optimization-based FDI methods which require many evaluations of gas turbine performance model, the fuzzy-based FDI method is a model-free approach, i.e. the engine performance model is not run during its operation, and this makes it possible to use the fuzzy-based FDI system in on-line applications.

Up to now, several studies have been conducted in the field of fuzzy-based fault diagnosis in gas turbines. Siu et al. [19] were

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