Mechanical Systems and Signal Processing 115 (2019) 255–268

Contents lists available at ScienceDirect

Mechanical Systems and Signal Processing

journal homepage: www.elsevier.com/locate/ymssp

Hybrid sequential fault estimation for multi-mode diagnosis of gas turbine engines

Houman Hanachi [a,b], Jie Liu [a,c,*], Il Yong Kim [b], Chris K. Mechefske [b]

[a] National Research Base of Intelligent Manufacturing Service, Chongqing Technology and Business University, Chongqing 400067, China
[b] Department of Mechanical and Materials Engineering, Queen's University, Kingston, ON K7L 3N6, Canada
[c] Department of Mechanical and Aerospace Engineering, Carleton University, Ottawa, ON K1S 5B6, Canada

ARTICLE INFO

Article history:
Received 10 July 2017
Received in revised form 14 March 2018
Accepted 27 May 2018

Keywords:
Fault estimation
Real-time diagnosis
Multi-mode diagnosis
Measurement noise
ANFIS

ABSTRACT

Health condition monitoring of Gas Turbine Engine (GTE) components is key for predictive maintenance planning. The task is challenging, as the gas-path components are mostly inaccessible for direct measurements, while at the same time hidden incipient faults must be diagnosed using the available measurements. The presence of multiple faults with similar symptoms adds to the complexity of the diagnostic process. In previous research work, a data-driven multi-mode fault parameter estimation scheme was introduced for real-time multimode diagnosis of GTEs under diverse operating conditions and fault scenarios. In this work, a hybrid diagnostic framework is developed that fuses the results from a measurement-based fault parameter estimation strategy together with a fault propagation model. The hybrid framework uses a novel particle filter (PF) structure with redundant measurements that facilitates updating the particle weights while reducing the dimensionality of the measurement likelihood. Applying the developed framework on GTE gas-path data with four different gradually worsening faults, the results show the diagnostic accuracy increases up to ten times, compared to the previously developed fault parameter estimation scheme.

1. Introduction

Due to the harsh operating environment, there are different degradation mechanisms within GTE components, leading to degradation of the parts and deterioration of the overall engine performance. Degradation of the parts increases the risk of mechanical failure, and deterioration of the performance leads to undesirable economical and environmental operating conditions, which is referred to as conditional failure. To avoid unexpected failure consequences, GTE operating companies attempt to acquire as much health-related information as possible through condition monitoring, and accordingly, schedule their maintenance services. It would be advantageous if one could predict the future health condition of the GTE parts, such that maintenance services can be conveniently scheduled before an imminent failure.

The two main parts of GTEs that experience different fault mechanisms are the compressor and the turbine sections. In GTE compressors, erosion of the blades and vanes leads to a gradual non-recoverable degradation, whereas the fouling phenomena causes a steep but recoverable degradation. Compressor degradation in either mode leads to loss of isentropic

* Corresponding author at: National Research Base of Intelligent Manufacturing Service, Chongqing Technology and Business University, Chongqing 400067, China.

E-mail address: jliu@mae.carleton.ca (J. Liu).

https://doi.org/10.1016/j.ymssp.2018.05.054
0888-3270/

Nomenclature

Symbols

ANFIS	adaptive neuro-fuzzy inference system
ANN	artificial neural network
a, b	prediction model parameters
D	dimension of state vector
EGT	exhaust gas temperature
e	diagnostic error
$F(.)$	state model
$f(.)$	probability density
$G(.)$	measurement model
GTE	gas turbine engine
$g(.)$	importance density
h	kernel bandwidth
$K(.)$	kernel density
k	time-step
m	number of particles
N	shaft speed
$NRMSE$	normalized root mean squared error
n	measurement redundancy
P	pressure
PF	particle filter
PW	power
RPF	regularized particle filter
SNR	signal to noise ratio
s	measurement signal
T	temperature
U	control input history
u	control input
V	ambient condition history
v	ambient condition
W	mass flow
x	health state
y	performance parameter
Y	performance history
Δt	length of time-step
$\delta(.)$	Dirac delta function
ε	measurement noise
η	isentropic efficiency
ρ	fault symptom
τ	process noise
ϕ	relative humidity
ω	particle weight
σ	standard deviation of noise

Subscripts

A	actual value
am	ambient
C	compressor
F	fuel
i	inlet
o	outlet
T	turbine

efficiency and a decrease of mass flow capacity for a given shaft speed and pressure ratio [1]. Degradation of the parts in the turbine section alters the turbine performance, mainly with a decline in the isentropic efficiency and a subtle increase in the mass flow capacity of the turbine, under a given pressure ratio and shaft speed [2,3]. Variations of isentropic efficiency and mass flow capacity are commonly used for quantification of the degradation in both compressors and turbines [4,5]. An obstacle is that, the component-level degradations (loss of isentropic efficiency and variation of mass flow capacity) are