Aerospace Science and Technology 56 (2016) 70–89

Contents lists available at ScienceDirect

Aerospace Science and Technology

www.elsevier.com/locate/aescte

Active Fault Tolerant Control with self-enrichment capability for gas turbine engines

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ARTICLE INFO

Article history:
Received 2 April 2016
Received in revised form 14 June 2016
Accepted 5 July 2016
Available online 14 July 2016

Keywords:
Active Fault Tolerant Control (AFTC)
Fault Detection and Identification (FDI)
Gas path deterioration
Gas turbine
Fuzzy logic
Global optimization

ABSTRACT

In this paper, an Active Fault Tolerant Control (AFTC) system with self-enrichment capability is proposed to deal with both the anticipated and unanticipated gas-path performance deteriorations in the industrial gas turbine engines. For this purpose, a hybrid fault diagnosis system with self-enrichment capability is proposed to take advantage of the positive features of fuzzy-based and global optimization-based Fault Detection and Identification (FDI) methods. The proposed FDI system provides the possibility of dealing with the unanticipated or unknown deteriorations. In order to design the proposed AFTC system, the parameters of the control system are optimized for a set of predefined deteriorations and through this a bank of control system parameters is created for the anticipated health conditions. The proposed FDI system verifies whether the detected health condition is an anticipated condition or not. In the case of the anticipated deteriorations, the proposed AFTC system selects the controller parameters from the bank of control system parameters, according to the current health condition; while in the case of the unanticipated deteriorations, the controller parameters will be determined through the optimization process. By adding the new set of optimized parameters to the bank of control system parameters, the database of the proposed AFTC system will gradually enrich to cope with a broader range of the engine deteriorations. The results obtained in the present work reveal that, the proposed AFTC system can preserve the engine safety and operational constraints; in the case of some deteriorations at the expense of a drop in the availability (due to a necessary trip or load shedding) and in some other cases even without losing the engine availability (by avoiding any unnecessary trip or load shedding). This is while, according to the results obtained, in the case of some health conditions, employing the controller designed for clean condition may cause the turbine over-temperature, loss of surge margin, and also a drop in the availability.

1. Introduction

Because of the demanding working conditions of the gas turbines, these systems may be affected by performance deteriorations over time, whose consequences may vary from partial loss of productivity and availability to full failure of the system. There are several factors that can affect the performance of the gas-path components of a gas turbine engine that among them, fouling and erosion [1–4] are usually considered as the most common cause of performance deteriorations. For more details about the physical origin of the common gas-path deteriorations and their effects on the overall performance of the gas turbine engines, please refer to Refs. [4–6].

The conventional control systems implemented on gas turbines, are often designed by this viewpoint that the gas turbines performance will remain unchanged during their lifetime. This is while, the gas turbine deterioration can change the static and dynamic behavior of the engine and therefore, the control system designed for clean condition, may not be able to meet all the engine control requirements.

Hence, it seems necessary to employ an efficient control method that can guarantee the performance and stability of the gas turbines in different health conditions. For this purpose, the control systems known as Fault Tolerant Control (FTC) systems [7–10], have been highly regarded in the last few years with the aim of providing the stability and performance of the controlled system in different health conditions.

Although, the most studies conducted in the field of the FTC systems, have been carried out with the aim of improving the performance of the aircraft flight control systems [10–14] and the nuclear facilities [15], nowadays, the growing demand to increase

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http://dx.doi.org/10.1016/j.ast.2016.07.003

Nomenclature

AFTC	Active Fault Tolerant Control
CAMF	Compressor air mass flow
CDCC	Controller Designed for Clean Condition
CDT	Compressor discharge temperature
CE	Compressor Erosion
CF	Compressor Fouling
EGT	Exhaust Gas Temperature
EWM	Enhanced Wiener Model
FDI	Fault Detection and Identification
FFDI	Fuzzy-based Fault Detection and Identification
FMF	Fuel Mass Flow
FST	Fault Signature Table
FTC	Fault Tolerant Control
GOFDI	Global Optimization-based Fault Detection and Identification
I/O	Input/output
IWO	Invasive weed optimization
MALL	Maximum Acceleration Limiting Loop
MDLL	Maximum Deceleration Limiting Loop
PFTC	Passive Fault Tolerant Control
PSO	Particle Swarm Optimization
T1E	Gas Generator Turbine Erosion
T1F	Gas Generator Turbine Fouling
T2E	Power Turbine Erosion
T2F	Power Turbine Fouling
VIGV	Variable Inlet Guide Vanes
$\bar{a}$	the radius of the neighborhood in defining the LB and UB
ACC-IDX	acceleration index
CPR	compressor pressure ratio
DEC-IDX	deceleration index
FAR	fuel–air ratio
FSM	flame stability margin
h	engine performance model
J	objective function
K_d	the derivative coefficient of the PID controller
K_i	the integral coefficient of the PID controller
K_p	the proportional coefficient of the PID controller
LB	lower bound of the optimization variables
M	the number of the measurement parameters
$\dot{m}$	mass flow rate
n	the number of the health parameters
N_{FST}	the number of the I/O pairs available in the fault signature table
NGG	gas generator rotor speed
NGGdot	acceleration of the gas generator turbine
$norm_i$	normalization factor
NPT	Power Turbine Rotor speed
OS-IDX	over-speed index
OT-IDX	over-temperature index
P	pressure
$\bar{P}$	power
PF	penalty function
REXT-IDX	rich extinction index
SF	scaling factor
SM	surge margin
SP	the total number of time-steps in the simulation conducted
SRG-IDX	surge index
t	time
T	temperature
Tol_i	the tolerances intended for the diagnosis procedure
UB	upper bound of the optimization variables
w	weighting factors
$\bar{w}$	power setting parameters
WEXT-IDX	weak extinction index
x	health parameter
$\hat{x}$	estimated health parameter
Δx	health parameter deviation from its clean condition
Y	parameters used in the component's map
z	measurement parameter
$\hat{z}$	estimated measurement parameter

Greek symbols

Γ	flow capacity
α	penalty factor
η	isentropic efficiency
θ_{VIGV}	the angular position of the variable inlet guide vanes
ϕ	equivalence ratio

Subscripts

ACC	acceleration
C	compressor
cl	clean (fault-free)
cor	corrected
DEC	deceleration
des	desired
det	deteriorated
dp	design point
GG	gas generator
GGT	gas generator turbine
i	gas turbine station number
init	initial
Map	component's characteristic curve
obs	observed
OL	operating line
PT	power turbine
RDL	red line value
ref	reference (ISA) condition
R	rich extinction
REL	rich extinction limit value
SL	surge line
st	the stoichiometric condition
W	weak extinction
WEL	weak extinction limit value
X	health parameter

the productivity, safety, and availability, has caused that the role of the FTC systems become more prominent in the other applications, such as: marine propulsion [16], automotive industry [17], and the other industrial equipment [18–23].

In a general classification, the FTC systems can be divided into two categories: active (AFTC) [9,10,24–27] and passive (PFTC) [28–30] systems. In the AFTC systems, the health condition of the controlled system will be identified through a Fault Detection and Identification (FDI) mechanism, and despite to the PFTC systems, the structure or the parameters of the control system may be changed to preserve the performance and stability of the whole system. No need to prioritize the faults, and no restrictions on the number of predefined fault scenarios, can be considered as the main advantages of employing the AFTC compared to the PFTC systems [31]. For more details about the distinction between the AFTC and PFTC systems, please see Refs. [31,32].

In the studies conducted in the field of the fault tolerant systems, some researchers [13] have used the term "AFTC" when referring to the self-repairing control systems; some of them [33] have used it for the reconfigurable control systems, while the others [34] have used this term for the restructurable control systems. Given that, the control system studied in this paper, is of the type of the reconfigurable control systems, thus in the present work, the term "AFTC" refers to this category of controllers.