Energy and Buildings 55 (2012) 252–263

Contents lists available at SciVerse ScienceDirect

Energy and Buildings

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

Online model-based fault detection and diagnosis strategy for VAV air handling units

Haitao Wang[a,c,d], Youming Chen[a,d,*], Cary W.H. Chan[b], Jianying Qin[b], Jinhua Wang[a,d]

[a] College of Civil Engineering, Hunan University, Changsha, Hunan 410082, China
[b] Swire Properties Management Ltd, Island East, Hong Kong, China
[c] College of Civil Engineering and Architecture, Henan University of Technology, Zhengzhou, Henan, China
[d] Key Laboratory of Building Safety and Energy Efficiency, MOE, China

ARTICLE INFO

Article history:
Received 18 February 2012
Received in revised form 8 August 2012
Accepted 15 August 2012

Keywords:
Variable-air-volume system
Air handling unit
Fault detection and diagnosis
Self-tuning model
Expert rules

ABSTRACT

An online model-based fault detection and diagnosis (FDD) strategy is presented in this paper to diagnose abrupt faults of variable-air-volume (VAV) air handling units (AHU). The FDD strategy proposed adopts a hybrid approach integrating model-based FDD method and rule-based FDD method. Self-tuning model is used to detect the faults in AHU systems. Model parameters are adjusted by a genetic algorithm-based optimization method to reduce the residual between prediction and measurement. If the residual exceeds the corresponding fault detection threshold, it indicates the occurrence of fault or abnormality in AHU systems. Meanwhile, an online adaptive scheme is proposed to estimate the fault detection threshold, which varies with system operating conditions. Furthermore, three rule-based fault classifiers are developed and utilized to find fault sources. The FDD strategy proposed was tested and validated on real VAV air-conditioning systems involving multiple faults. The validation results show that the FDD strategy proposed can provide an effective tool for detecting and diagnosing the faults of air handling units.

1. Introduction

Variable-air-volume (VAV) air-conditioning system is one of the most energy-efficient and comfortable systems for buildings. However, VAV air-conditioning systems tend to have more faults due to the complexity of their control systems. Faults in VAV air-conditioning systems will bring about abnormal operations which subsequently increase energy consumption of the systems, deteriorate indoor thermal comfort, and decrease the service life of air-conditioning equipments. 20–30% of the energy consumption of heating, ventilation and air conditioning (HVAC) systems in commercial buildings is wasted because of faults and non-optimal operations [1]. A successful fault detection and diagnosis (FDD) can save 10–40% of HVAC energy consumption [2–4], which depends on the age and condition of the equipment, maintenance practice, climate and building use. FDD techniques have been proved to be an essential and efficient supporting tool in timely fixing faults and reducing the negative impacts of faults. Therefore, it is significant to develop suitable FDD methods that can be used in VAV air-conditioning systems [5].

In most large air-conditioned buildings, air handling units account for a significant portion of total building energy consumption and have a major impact on comfort condition. Extensive researches have been conducted on the FDD for air handling units during the past three decades. House et al. [6] demonstrated the application of several classification techniques to the problem of diagnosing faults in the data generated by a VAV AHU simulation model. Wang and Xiao [7] used principal component analysis (PCA) method to detect and diagnose the sensor faults in air handling units. Lee et al. [8] used general regression neural-network (GRNN) models to detect the faults in air handling units. Schein et al. [9] used a set of expert rules, derived from mass and energy balances, to detect the faults in air handling units. Yang et al. [10] used some expert rules to detect and diagnose the sensor faults in AHU systems. Yoshida et al. [11] developed dynamic FDD models for VAV air handling units using recursive autoregressive exogenous algorithm. Xiao and Wang [12] presented an online fault diagnosis tool for online sensor heath monitoring and fault diagnosis of AHU systems. Yang et al. [13] used fractal correlation dimension (FCD) to detect supply air temperature sensor faults in air handling units. Fan et al. [14] presented a hybrid FDD strategy for local systems of air handling units. Back-propagation neural network (BPNN) models, wavelet analysis and Elman neural network were used to diagnose the faults in air handling units. Song et al. [15] developed an easy-to-use tool for

* Corresponding author at: College of Civil Engineering, Hunan University, Changsha, Hunan 410082, China. Tel.: +86 731 88823515; fax: +86 731 88823515.
E-mail address: ymchen@hnu.edu.cn (Y. Chen).

0378-7788/$ – see front matter
http://dx.doi.org/10.1016/j.enbuild.2012.08.016

Nomenclature

a_i	tuning model parameter
d	fan diameter
E_i	prediction
K	heat transfer coefficient
M_i	measurement
N	fan speed
P_{fan}	fan static pressure
P_{mix}	mixing plenum static pressure
$P_{sa,pr}$	predicted supply air static pressure
Q	heat transfer rate
R	heat resistance
T	temperature
U_{cc}	measured cooling coil valve opening (0–1)
V	flow rate
W	air humidity ratio
x_0	model input vector
X_{reg}	matrix of the model development data

Greek symbols

δ_{ref}	reference value
ε_{vp}	error threshold of cooling coil valve opening
ε_f	error threshold of air flow
ε_p	error threshold of supply air pressure
ε_t	error threshold of supply air temperature
ε_{tw}	error threshold of chilled water supply temperature
φ	dimensionless coefficient of flow
λ	dimensionless coefficients of shaft power
θ	forgetting factor
ρ	air density
$\sigma^2_{Y_i}$	total variance of the residuals of the *i*th model output variable
ξ	dimensionless coefficients of pressure head

Subscript

a	air
cc	cooling coil
cw	chilled water
des	design
en	entering
ex	external
h	enthalpy
in	internal
le	leaving
ma	mixed air
oa	fresh air
pr	predicted
ra	return air
sa	supply air
sen	sensible
set	setpoint
tot	total

fault detection and diagnosis of air-conditioning systems. Ghiaus [16] used the qualitative bond graph method to detect the faults in air-conditioning systems. Wang and Jiang [17] used cerebellar model articulation controller (CMAC) neural networks to monitor and diagnose the performance degradation of cooling coil valves. Peitsman and Soethout [18] described the application of ARX models to the fault diagnosis of air handling units. Norford et al. [19] presented two methods for detecting and diagnosing the faults in AHU systems. One of the FDD methods used a first-principle-based model for system component, and the second method was based on semi-empirical polynomial correlations of sub-metered electrical power with flow rates or process control signals generated from historical data. Carling and Haves [20] presented a comparison of three fault detection methods for AHU systems. The three methods included a qualitative method that compared controller outputs and model-based predictions, a rule-based method that examined measured temperatures and controller outputs, and a model-based method that analyzed residuals based on steady-state models. All methods above-mentioned were specifically developed for detecting and diagnosing the faults in AHU systems. Some of these FDD methods can detect and diagnose the faults in air handling units automatically. However, current energy management and control systems (EMCS) do not have the FDD function for HVAC systems yet. Few efforts were made on the analysis of real-time HVAC operating data and the implementation of online FDD in real air handling units.

Since the reliable control of overall VAV air-conditioning system depends on correct operation of every component, researchers began to pay attention to the fault diagnosis of VAV terminals in recent years. Schein and House [21] presented a fault detection method using control charts to detect the faults in VAV terminals. The fault detection method successfully detected all faults introduced in the emulation and laboratory testing, and detected two faults that were not intentionally implemented. Wang and Qin [22,23] utilized expert rules, performance indexes, statistical process control models and PCA method to diagnose the faults in VAV terminals. Seem et al. [24] looked into VAV terminal on-line controls. Two indices calculated from the operating data were used for online detecting and diagnosing faults of VAV terminals. Wang et al. [25,26] presented an online fault diagnosis tool for VAV terminals. The fault diagnosis tool was integrated with the EMCS system and validated in a real office building.

The above literature survey shows that the research on FDD for VAV air-conditioning systems is still insufficient. Few current methods are suitable for the implementation of online FDD in real VAV air-conditioning systems [27,28]. Large amounts of real-time operating data available in the EMCS systems provide the chance for online FDD of HVAC systems. The study on online FDD of HVAC systems has already received increased attention recently [29]. The FDD methods for AHU systems should be developed according to its special operational characteristics. AHU systems are operated under diverse weather and internal load conditions. Hence, The FDD methods should be robust enough to cope with the dynamic characteristics of an AHU system. Moreover, FDD methods should require no additional sensors and be computationally efficient to be implemented online. Generally, FDD methods can be divided into two types: the model-based FDD method and the data-driven FDD method [30]. As for the model-based FDD method, the single most important factor is the need for accurate and reliable models of HVAC systems. A number of HVAC component models have been proposed during the past two decades for system optimal control [15]. However, these models are not suitable to fault detection for AHU systems as the fault detection method requires more accurate and reliable models. Nassif et al. [31] presented self-tuning dynamic HVAC component models to optimize HVAC system controls. Validation results show that the modeling accuracy of the self-tuning dynamic HVAC component model is higher than that of the pure physical model without the tuning parameters.

In this paper, a fault detection and diagnosis strategy for VAV air handling units is presented by integrating the model-based FDD method and the rule-based FDD method. A fault detection method based on self-tuning dynamic AHU models is proposed to detect the faults of VAV air handling units. This new fault detection method can cope with the dynamic characteristics of the AHU system well, which can improve the accuracy of fault detection. Meanwhile, three rule-based fault classifiers are developed and