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Energy and Buildings 37 (2005) 1035–1048
ENERGY and BUILDINGS
www.elsevier.com/locate/enbuild

A fault detection and diagnosis strategy of VAV air-conditioning systems for improved energy and control performances

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Received 19 October 2004; received in revised form 8 December 2004; accepted 24 December 2004

Abstract

This paper presents the results of a site survey study on the faults in variable air volume (VAV) terminals and an automatic fault detection and diagnosis (FDD) strategy for VAV air-conditioning systems using a hybrid approach. The site survey study was conducted in a commercial building. 20.9% VAV terminals were ineffective and 10 main faults were identified in the VAV air-conditioning systems. The FDD strategy adopts a hybrid approach utilizing expert rules, performance indexes and statistical process control models to address these faults. Supported by a pattern recognition method, expert rules and performance indexes based on system physical characteristics are adopted to detect 9 of the 10 faults. Two pattern recognition indexes are introduced for fault isolation to overcome the difficulty in differentiating damper sticking and hysteresis from improper controller tuning. A principal component analysis (PCA)-based method is developed to detect VAV terminal flow sensor biases and to reconstruct the faulty sensors. The FDD strategy is tested and validated on typical VAV air-conditioning systems involving multiple faults both in simulation and in situ tests.

Keywords: Variable air volume system; VAV terminal; Fault detection and diagnosis; Commissioning; Principal component analysis

1. Introduction

Variable air volume (VAV) air-conditioning system, which is deemed more economical than other alternative systems, has been widely adopted in the buildings to maintain the cooling and heating demands. However, in complex VAV systems, faults at system level, subsystem level, component level, control and sensor level would not only reduce the economic benefits of the system but also lead to occupant discomfort. Though the benefits for fault detection and system improvement are difficult to quantify, the potential savings out of faulty and non-optimal operation of HVAC system alone in commercial buildings were estimated to be 20–30% [1].

Faults typically found in air-conditioning systems are due to improper design, application or operation of the systems [2]. A survey was conducted to sort out the top 10 faults of air-conditioning systems by collecting information from professionals [3]: (1) poor air quality, (2) water leakage, (3) room air temperature deviation due to excessive heat generation, (4) room air temperature deviation due to inadequate air-flow rate, (5) too much or less air volume of VAV unit, (6) excessive pressure difference across an air filter, (7) abnormal noise or vibration, (8) room air temperature deviation due to inadequate positions of diffusers, (9) false opening signal to a VAV unit control and (10) room air deviation due to insufficient water flow rate. Further investigation revealed that mechanical faults (such as coil and damper malfunction) were common also [3].

Fault detection and diagnosis (FDD) has been approved to be an essential and efficient supporting tool in fixing faults timely and reducing the impacts of them in building HVAC applications. However, previous FDD studies focused on the major equipment of the systems, such as air handling units (AHUs), fans and local feed water pumps. Various systems and methods were studied and developed. Lee et al. [4]

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doi:10.1016/j.enbuild.2004.12.011

Nomenclature

A	network relationship matrix (for nodes)
B	basic circuit matrix (for circuits)
e	process error
F	air flow rate
ΔF	air flow variation
G	vector of flow rate (G_1, G_2, ..., G_n)
H	vector of pressure increments caused by fan in the branch (H_1, H_2, ..., H_n)
P	pressure
$\boldsymbol{P}$	principal loading matrix
ΔP	vector of pressure difference in the branch (ΔP_1, ΔP_2, ..., ΔP_n)
R	reversal
SPE_α	threshold of SPE
S	vector of resistance coefficient (S_1, S_2, ..., S_n)
t	time
T	temperature
T^2_α	threshold of T^2 statistic
TF	total flow
X	variable matrix
y	process variable
ΔZ	vector of pressure difference caused by altitude difference in the branch (ΔZ_1, ΔZ_2, ..., ΔZ_n)

Greek letters

α	weighting factor
Λ	matrix of eigenvalues
μ	control signal to terminal damper
σ	standard deviation

Subscripts and superscripts

a	number of PCs
delt	permissive period
F	air flow rate
k	kth variable
max	maximum
min	minimum
new	new samples
set	set-point
st	static
th	threshold
^	estimated output on the score space
–	estimated output on EWMA

generally described 11 faults of a system from fan failure to sensor failure and the use of a two-stage artificial neural network for fault diagnosis in a simulated AHU. Results demonstrated that the recovered estimate of the supply air temperature could be used in a feed-back control loop to bring the supply air temperature back to the set-point value. Dexter et al. [5–8] concentrated on coil heat exchange process of AHUs and analyzed five faulty modes: fouled coil, valve leak, valve stuck closed, valve stuck midway and valve stuck open. They designed a robust fuzzy model for AHU fault diagnosis accounting the temperature sensor error. The model-based approach was successfully applied in a fault diagnosis scheme to remotely commissioning AHUs in a commercial building. Norford et al. [9,10] investigated both abrupt and degradation faults on several sections of three existing AHUs and proposed two methods for FDD, i.e. physical model-based method and grey box method. Both methods detected nearly all of the faults in the two matched AHUs. House et al. [11] studied several faulty cases of an AHU. Five classifiers, i.e. ANN classifier, nearest neighbour classifier, nearest prototype classifier, rule-based classifier and Bayes classifier, were tested for detecting and diagnosing seven faults of a simulated AHU system. They also proposed an expert rule set with 28 simple rules for fault detection in AHUs [12]. Field trials of the expert rule set successfully identified two occurrences of faults with mixing box dampers while they pointed out that the effort devoted to developing diagnostic capabilities for VAV boxes had been limited in comparison to AHUs and other types of HVAC equipment [13].

Researchers also paid more attention on subsystems in the recent years. Katipamula et al. [14,15] noticed that a failure of the economizer might go completely unnoticed. They designed an 'outdoor-air/economizer diagnostician' to monitor the performance of AHUs and automatically detect problems with economizer operation or ventilation problems for systems without economizers using decision tree method. Dodier et al. [16] particularly studied on fan-powered mixing box for both damper failure and power failure. The probabilistic inference methods were adopted in real-time diagnostic system (RTDS). The results of applying the RTDS to HVAC laboratory data were presented. The tests indicated that application of this inference system to the diagnosis of mixing box failures yielded encouraging results. Wang and Chen [17] paid particular attention to the air flow sensor failure of sensor-based demand control ventilation systems. They pointed out that fault-tolerant control for outdoor ventilation air flow rate based on neural network was applicable.

As overall system reliable control relies on proper works of every component, few researchers began to particularly focus on VAV terminals and valves. Seem et al. [18] looked into VAV terminal on-line control recently. Two indexes were calculated from building management system (BMS) driven data for VAV box on-line monitoring and fault detection. A diagnostic method using a small number of cumulative sum statistical quality control charts to assess the performance of VAV boxes was proposed by Schein and House [19] afterwards. It had been embedded in commercial HVAC controllers and successfully tested using emulation and laboratory data. In the study, the faults detected are focused on damper stuck and oscillation. Multiple conflicting faults had not been identified. Yoshida et al. [3,20,21]