Fuzzy Logic Control and Fault Detection in Centralized Chilled Water System

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***Abstract*—The objective of this work is to develop and implement a fuzzy controller and fuzzy fault detection for centralized chilled water system. Both controller and fault detector are implemented in air supply dampers of air handling unit (AHU). A few cases are tested in this paper to investigate the effectiveness of the developed systems. All simulation is carried out using MATLAB/SIMULINK. Results illustrate that the fuzzy controller is able to maintain room temperature according to that desired whereas the fault detection can detect unusual behavior in supply air flowrate.**

I. INTRODUCTION

Fuzzy systems can be used to estimate any real function on a compact fuzzy subset [1]. Fuzzy system is a rule-based method where the rule set learns from an expert's experience or prior knowledge of the system. Because of its simpler implementation and reduced design costs, fuzzy system is widely used and successfully implemented in the area of control, forecasting, plant monitoring and diagnosing [2]. However, reviews from [1, 3] show that not many fuzzy system are used in the application of HVAC control and fault detection as compared to other area.

Eftekhari, Marjanovic and Angelov [4] designed a fuzzy controller for naturally ventilated buildings and validated it at a real building test room. Results show that fuzzy controller can provide better thermal comfort in the test room by adjusting the opening of the air ventilation according to the outdoor weather conditions. A self-tuning fuzzy control algorithm was developed by Wu, Xingxi and Chen [5] in multi-evaporator air conditioners such as variable refrigerant volume technology. Controllability test shows that the proposed algorithm is sufficient to achieve the required result. On the other hand, the performance of three and five membership functions of fuzzy logic controller for centralized chilled water system has been investigated by Sulaiman, Othman and Abdullah [6]. Results have shown that both types of controller are almost equal in performance.

The application of fuzzy logic controller is not limited to building air conditioning system but in car air conditioning as well. For instance, Othman and Othman [7] compared the application of fuzzy logic control and state flow controller in the perspective of car air conditioning. Fuzzy logic control shows encouraging and better performance than the latter controller.

Meanwhile, fuzzy system is also successfully employed in fault detection as in [8-11]. Safarinejadian, Ghane and Monirvaghefi [8] proposed a new method for fault detection based on interval type-2 fuzzy sets for two-tank system. The result shows that beside of the ability of the proposed method to detect faults, its computation time to find interval bound is faster than adaptive-network-based fuzzy inference systems (ANFIS) method. Whilst in the HVAC area, a few researchers have proposed fuzzy system as a fault detection and diagnosis method as in [10-11]. Lo, Chan, Wong, Rad and Cheung [11] proposed an intelligent technique based on fuzzy-genetic algorithm (FGA) for automatically detecting faults in the HVAC system.

In this paper, performances of fuzzy logic controller and fault detection are analyzed in the context of centralized chilled water system. One fuzzy logic controller and two fuzzy fault detection systems were developed for air supply damper in air handling unit (AHU). The overall system has two zones with the same properties and dimension. The performances of both controller and fault detection at both zones are investigated in different cases. Results show that both developed systems can respond well to the given input.

A detail of system description used in this paper is explained in Section II. It includes hardware and modelling

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parts of the system. Then, the following section, Section III, describes the methodology of this work. In Section IV, results are discussed and analyzed, whereas Section IV concludes the overall findings of this paper.

II. System Descript

In this work, lab scale chilled water system and modeling of the system were constructed and developed

A. Lab Scale Chilled Water System

A lab scale of chilled water system was developed which consists of water cooled chiller, cooling tower, air handling unit (AHU) and two test rooms. The water cooled chiller system has a chilled water tank in between its chiller and AHU. The cooling tower is designed as a counter flow type. In AHU system, it has cooling coil, two sets of damper; one for each supply duct, supply and return ducts for each test room and a fan. The test rooms were constructed using insulated board and poly-carbonate and each of it sizes was 2.4m × 1.2m × 1.6m. The supplied air flow rate is controlled by varying the damper position. Moreover, the supplied air flow rate and returned room temperature are used as the input to fault detection.

Nomenclature

M	heat mass capacitance
C_v	specific heat at constant volume
ρ	air density
C_p	specific heat at constant pressure
Q	volumetric flow rate
T	temperature
U	overall heat transfer coefficient
A	Area
h_{fg}	latent heat of water
w	humidity ratio
subscripts;	
cc	cooling coil
a	air
tr	test room
s	supply air
amb	ambient air
w	water
$chws$	chilled water supply
t	chilled water tank

B. Modelling of the system

The mathematical modelling of each component in the system was derived based on the lumped capacitance method as described in [12]. It is assumed that air velocity and room temperature are uniform in each test room. Furthermore, humidity and indoor air quality are not controlled.

The temperature of the test room is derived based on the supplied air, returned air, heat from the ambient and internal heat as follows.

$$M_{tr} C_v \frac{dT_{tri}}{dt} = \dot{m}_a C_{p_a}\left(T_s - T_{tr_i}\right) + \dot{\theta}_{\text{int}} + U_{tr} A_{tr}\left(T_{amb} - T_{tr_i}\right). \quad (1)$$

where $i = 1, 2$.

The heat between chilled water and air is exchanged in the cooling coil of AHU. The modelling of the cooling coil is expressed as;

$$\begin{aligned} M_{cc} C_v \frac{dT_s}{dt} &= \rho_a C_{p_a} Q_m (T_m - T_s) \\ &+ U_{cc} A_{cc} (T_{amb} - (T_s + T_m)) \\ &+ Q_w \rho_w C_{p_w} (T_{chws} - T_t) \\ &+ (h_{fg} - C_{p_a}) \rho_a Q_m (w_{tr} - w_s) \end{aligned} \quad (2)$$

The temperature of chilled water tank is modelled as follows.

$$\begin{aligned} M_t C_{pw} \frac{dT_t}{dt} &= U_t A_t (T_{amb} - T_t) + \dot{\theta} \\ &+ Q_w \rho_w C_{p_w} (T_{chws} - T_t) \end{aligned} \quad (3)$$

III. Methodology

A fuzzy logic controller was designed to settle room temperature and two fuzzy logic fault detection to identify any fault in this simulation work. Each room has its own damper to simulate multi-fault condition.

A. Temperature Controller

Test room temperature control loop was designed in this study. By comparing the values of room temperature with their set point value, the controller adjusted the amount of supply air flow rate that entered the test rooms. In that way, both rooms' temperature can be set to their desired temperature values. From (1), it shows that room temperature is related to the quantity of supply air flow rate that enters the test room. From experimental setup, the relation between supply air flow rate, Q_a and the position of the supply air damper, u, was obtained as follow;

$$Q_a = \begin{cases} 0.058u - 0.00814, \text{For u} > 17\% \\ 0, \text{For } u \le 17\% \end{cases} \quad (4)$$

The quantity of supply air flow rate can be controlled by varying the position of the damper up to 90°. Therefore, the control inputs of the controller were temperature errors of both test rooms, ΔT_1 and ΔT_2. The outputs of the controller were the damper position, u_1 and u_2. Fuzzy logic controllers from [6] were improved and used in the simulation. Details of the quantization level and rules for this controller are tabulated in Tables I, II and III.

B. Fault Detection

In this paper, faults related to supply air dampers were considered and analyzed. These types of faults are categorized as degradation fault and it may affect the control process and performance of the system.

Two fault detection systems were developed using fuzzy logic for both test rooms. These systems were to detect any unusual process that may occur during the operation of the system. It compared between its process and normal behavior. Three indicators were used which were "no fault"," almost fault" and "fault". "No fault" represents the process behavior as being similar to that of its normal behavior. In addition, "almost fault" corresponds to process behavior that was in between 30% to 50% different from its normal behavior. Whereas "fault" indicates that the system was having a problem.

The shapes of the input and output membership functions used in this work were a combination of trapezium and triangle. Details regarding the quantization level of its membership function and fuzzy rules are listed in Tables IV and V.

C. Simulations

Simulations were done using MATLAB/SIMULINK on for t = 400s. Some parameters were set constant throughout the simulations as in [6, 13]. The reference set point temperature was set as 24°C which follows the Malaysian Standard (MS 1525:2007) requirement.

Different faults have different effects on the system operation. It consists of one fault-free and two different faults cases as described in Table VI. Case 1 represents normal operation of both dampers. In a normal operation, dampers are free to swing from fully closed, 0° to fully opened, 90°. Case 2 means that damper 1 has restriction to swing to fully open position at 90° but damper 2 operates normally. Damper 1 can only swing from 0° to 30°. Lastly, Case 3 represents one damper working fine but the other is stuck at about 45°. The analysis and discussion for all cases are presented in Section IV

TABLE I. QUANTIZATION LEVEL FOR ROOM TEMPERATURE CONTROLLER

Type	No. of member ship function	Quantization level
Input 1: Temperature difference of room 1	5	Negative Big (NB) Negative Small (NS) Zero (ZE) Positive Small (PS) Positive Big (PB)
Input 2: Temperature difference of room 2	5	Negative Big (NB) Negative Small (NS) Zero (ZE) Positive Small (PS) Positive Big (PB)
Output 1: Position of damper 1	5	Very Big (VB) Big (B) Medium (M) Small (S) Very Small (VS)
Output 2: Position of damper 2	5	Very Big (VB) Big (B) Medium (M) Small (S) Very Small (VS)

TABLE II. RULES FOR DAMPER 1, U_1

ΔT_1 / ΔT_2	***NB***	***NS***	***ZE***	***PS***	***PB***
NB	VB	B	M	S	S
NS	VB	B	S	S	VS
ZE	B	M	S	VS	VS
PS	B	M	VS	VS	VS
PB	M	M	VS	VS	VS

TABLE III. RULES FOR DAMPER 2, U_2

ΔT_1 / ΔT_2	***NB***	***NS***	***ZE***	***PS***	***PB***
NB	VB	VB	B	B	M
NS	B	B	M	M	S
ZE	M	S	S	VS	VS
PS	S	S	VS	VS	VS
PB	S	VS	VS	VS	VS

TABLE IV. QUANTIZATION LEVEL FOR FAULT DETECTION

Type	No. of member ship function	Quantization level
Input 1: Temperature difference	5	Negative Big (NB) Negative Small (NS) Zero (ZE) Positive Small (PS) Positive Big (PB)
Input 2: Position of damper	5	Very Big (VB) Big (B) Medium (M) Small (S) Very Small (VS)
Output: Fault detection	3	No fault (0) Almost fault (0.5) Fault (1)

TABLE V. RULES FOR FAULT DETECTION

ΔT / u	*NB*	*NS*	*ZE*	*PS*	*PB*
VS	1	1	0.5	0.5	0
S	1	0.5	0	0	0.5
M	0	0	0	0.5	1
B	0	0	0.5	1	1
VB	0	0.5	1	1	1

TABLE VI. LIST OF CASES CONSIDERED IN THIS PAPER

Cases	Operating cases
Case 1	Normal operation without fault
Case 2	Damper 1 can only swing up to 30° of opening position, while damper 2 is normal
Case 3	Damper 1 is normal while damper 2 stuck at 45° of opening position

IV. RESULTS AND DISCUSSION

A. Case 1

In this case, all components in the system were operated normally. It was assumed that both dampers 1 and 2, operated in normal condition where they were free to swing up to the full opening which was 90°. However, the opening was controlled by its controller according to the test rooms' temperature throughout the simulation. Fig. 1 represents the temperature variation for test rooms 1 and 2. The simulation results showed that both test rooms were cooled down from 30°C to 24°C for about three minutes and thirty seconds. Apparently, there were no steady state errors as compared to [6]. As a result, there was no fault detected in both dampers as shown in Fig. 2.

B. Case 2

The second case simulated was that one of the dampers cannot fully function which means it can only swing up to a certain position. In this case, it was assumed that damper 1 can only swing up to 30° of its opening position, while damper 2 functioned as normal. Despite of damper 1 having a problem, both test rooms were able to settle at 24°C. From Fig. 3, it shows that test room 1 was able to be cooled down from 30°C to 24°C around six minutes and forty seconds as compared to three minutes in test room 2. The limited opening of damper 1 caused test room 1 to receive lesser amount of supply air whilst test room 2 received more than usual in the beginning. As a result, the cooling down time for test room 1 required longer time and test room 2 was slightly faster than those in case 1.

As room 1 received unusual amount of air flow rate in the beginning, thus, fault was detected in damper 1. However, since damper 1 can still swing even up to only 30°, both rooms eventually can be cooled down to its set point temperature. This explained the reason why the fault subsided later in time. The details of fault detection in both dampers were portrayed in Fig. 4.

C. Case 3

Case 3 was simulated with the assumption that damper 1 worked normally while damper 2 was stuck at 45° of the opening position. It was expected that the damper was stuck throughout the simulation. Fig. 5 illustrates the temperature variation in both rooms during the simulation. The temperature in test room 1 behaved similarly as the one in Case 1. However, the temperature in test room 2 was not able to be settled at the required value because the room still received constant amount of cold supply air even when it has cooled down.

Fig. 6 displays fault detection for both dampers in this case. Since the temperature in test room 1 behaved normally, no fault was detected in damper 1. Initially, no error was detected in damper 2 as it still complied with rules in Table III. However, since the room continually received a constant amount of cold supply air, the difference between actual and normal supply air flowrate was getting bigger from time to time. Therefore, the system finally detected that the damper was faulty after around two minutes and thirty seconds.

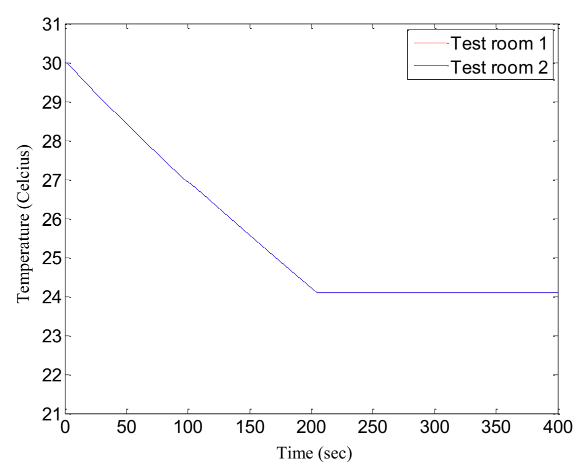

Fig. 1. Temperature variation in test room 1 and test room 2.

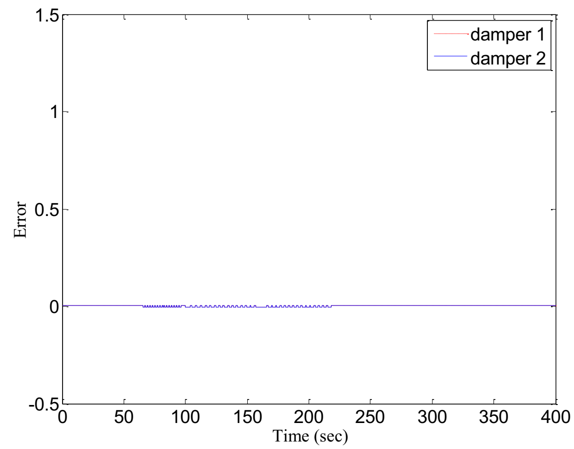

Fig. 2. Fault detection for damper 1 and damper 2.

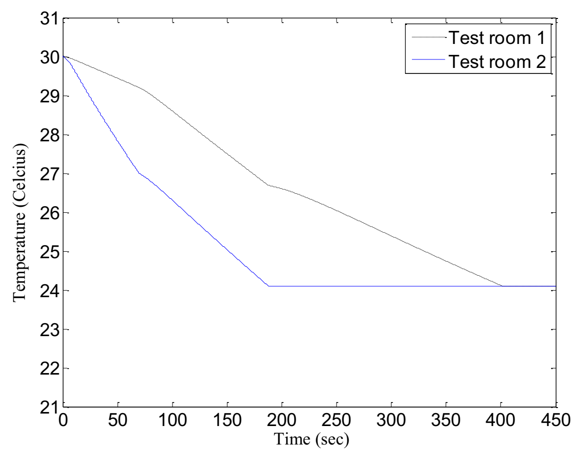

Fig. 3. Temperature variation in test room 1 and test room 2.

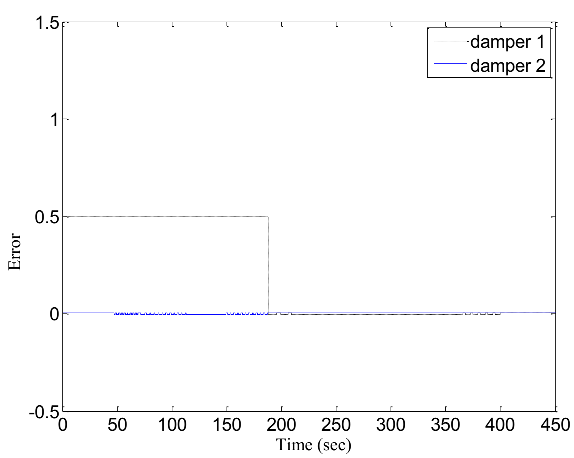

Fig. 4. Fault detection for damper 1 and damper 2.

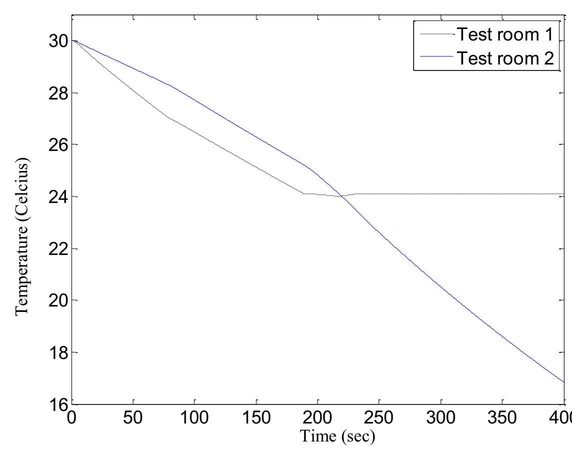

Fig. 5. Temperature variation in test room 1 and test room 2.

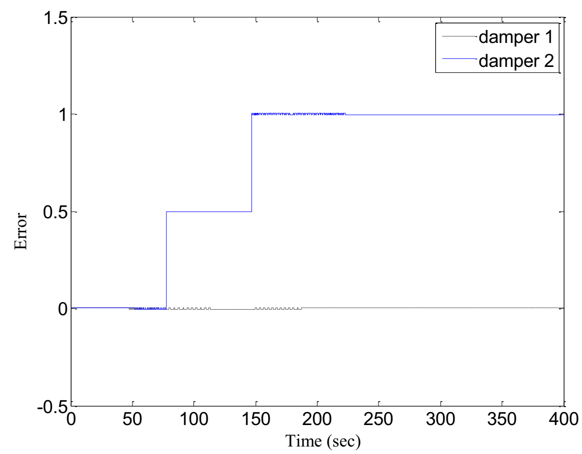

Fig. 6. Fault detection for damper 1 and damper 2.

D. Detection Time

Detection time of faults simulated in this paper was summarized in Table VII. Case I is a fault-free case, hence no fault detected during simulation. For Case 2, the system detected 'almost fault' condition immediately when simulation ran. However, the fault subsided later on when the system performance recovered as normal. As for Case 3, the first detection time was around 1.3 minutes. At first it detected as 'almost fault' which means the system detected an error but the performance of the system was still acceptable. Later, when the error got bigger and the performance was unacceptable, a fault alarm was triggered. All faults were introduced to the system from the beginning of the simulation.

TABLE I. DETECTION TIME

Cases	Detection time
Case 1	Not applicable
Case 2	0 min
Case 3	1.3 min

V. Conclusion

This paper presents the results of fuzzy logic controller and fuzzy fault detection in the context of centralized chilled water system. Three operating cases were examined through two test rooms with some parameters were set constant throughout the simulations. Results show that the controller was able to cool the test rooms to the desired temperature values. Moreover, the fault detection system corresponded well to faults induced to the damper.

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