Energy and Buildings 43 (2011) 805–813

Contents lists available at ScienceDirect

Energy and Buildings

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

Nonlinear multivariable control and performance analysis of an air-handling unit

Hamed Moradi*, Majid Saffar-Avval, Firooz Bakhtiari-Nejad

Energy and Control Centre of Excellence, Department of Mechanical Engineering, Amirkabir University of Technology, Tehran, Iran

ARTICLE INFO

Article history:
Received 26 September 2010
Received in revised form 4 November 2010
Accepted 25 November 2010

Keywords:
Air-handling unit
Nonlinear model
Multivariable control
Tracking
Gain scheduling
Feedback linearization

ABSTRACT

To maintain satisfactory comfort conditions in buildings with low energy consumption and operation cost, control of air-conditioner units is required. In this paper, nonlinear control of an air-handling unit (AHU) is investigated and compared for two control approaches: gain scheduling and feedback linearization. A nonlinear multi input–multi output model (MIMO) of an air-handling unit (AHU) is considered. Both indoor temperature and relative humidity are controlled via manipulation of valve positions of air and cold water flow rates. Using an observer to estimate state variables, a hybrid control system including regulation system for disturbance rejection and nonlinear control system for tracking objectives is designed. Achievement of tracking objectives is investigated for various desired commands of indoor temperature and relative humidity; including a sequence of steps and ramps-steps. According to results, more quick time responses with a bit more overshoot in tracking set-points/paths are achieved by using feedback linearization method (especially for temperature). However, valves position as input control signals are associated with less oscillation (and consequently less energy consumption) when the controller designed based on gain scheduling approach is used. Finally, it is shown through phase portrait of the system that the controller designed based on feedback linearization shows a robust performance in the presence of random uncertainty in model parameters.

1. Introduction

With the improvement of standard of living, air-conditioning systems are extensively used to provide comfort and acceptable indoor air quality (IAQ). A comprehensive review on air-conditioning systems and indoor air quality control to preserve human health has been done [1]. Since energy and operation costs of buildings are directly influenced by how well an air-conditioning system perform, effective thermal management is of great importance. It is estimated that avoidable energy waste in buildings is about 20–50% and that 15% of the energy waste can be recovered by effective control of the air-conditioning system [2,3].

Air-handling units (AHU) have an essential role for providing supply air with specific temperature and humidity in heating, ventilating and air-conditioning (HVAC) operations. At the design stage, for studying the system performance, finding an approximate mathematical model of system components is essential. However, due to the complex nonlinear nature of an AHU with multivariable parameters and time varying characteristics of its components, finding an exact mathematical model is difficult [4]. For testing, commissioning and evaluating control strategies implemented in energy management and control systems (EMCS), dynamic simulation of HVAC systems is a convenient and low cost tool.

Several investigations have been accomplished for dynamic modelling and simulation of HVAC systems and its components. Dynamic model and transient response for space heating and cooling zones [5] and dynamic simulation and evaluation of EMCS on-line [6,7] for variable air volume (VAV) air-conditioning systems have been presented. Using automatic data acquisition system for on-line training and artificial neural network [8] and grey-box identification approach [3], air-handling unit has been modelled.

In addition, in other works of this area, a dynamic model of cooling coil unit (the basic element in AHU unit) has been developed by extending the engineering model and combining with the mass and energy balance equations [9]. Recently, simulation of a VAV air-conditioning system for the cooling mode has been carried out through an energetic study [10] (including several references dealing with innovative work on VAV). Also, an overview of current approaches used for modelling and simulation of HVAC systems including control aspects has been presented [11].

Improving system energy efficiency (by reducing energy consumption) and indoor comfort conditions are major concerns in any HVAC control system. Many control strategies have been implemented to improve dynamic behaviour of air-conditioning systems. Model based analysis and simulation of airflow control of AHU units using PI controllers [12], multivariable control of indoor air quality in a direct expansion air-conditioning system [13] and control tuning of a simplified VAV system [14] have been studied. Also, cascade control algorithm and gain scheduling [15], analysis of dif-

---

* Corresponding author. Tel.: +98 21 64543417; fax: +98 21 66419736.
E-mail address: hamedmoradi@mech.sharif.ir (H. Moradi).

0378-7788/$ – see front matter © 2010 Elsevier B.V. All rights reserved.
doi:10.1016/j.enbuild.2010.11.022

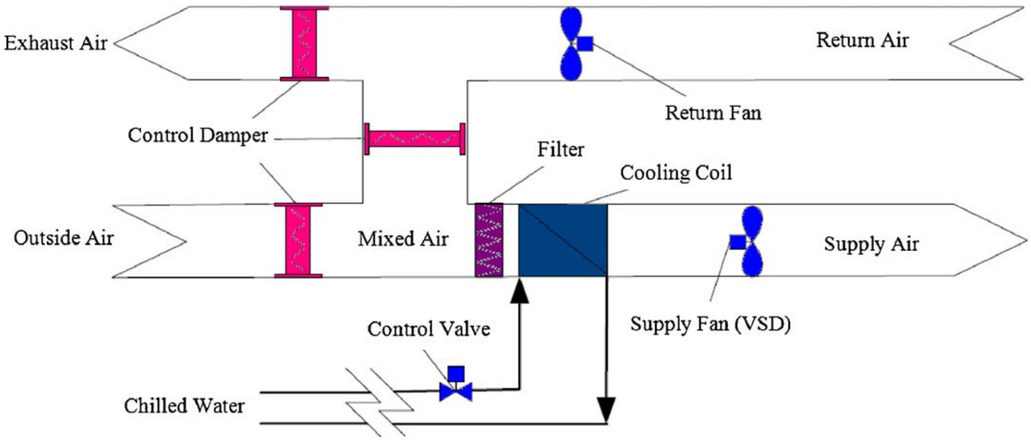

Fig. 1. Schematic view of an air-handling unit having one zone (indoor) in VAV system.

ferent control schedules on EMCS [16] and model predictive control [17] of air-handling units have been investigated.

In other control strategies, rule development and adjustment of a fuzzy controller [18], fuzzy control optimized by genetic algorithms (GA) [19], using a combination of artificial neural fuzzy interface modelling and a PID controller [20] and developing an adaptive fuzzy controller based on GA [21] have been implemented on air-handling units. In addition, optimal control [22], proportional optimal control [23] and adaptive self-tuning PI control [24] are other control approaches used for HVAC systems.

Since tuned control parameters cannot cover all the operating range of the air-conditioning systems, using traditional control approaches may result in aggressive or sluggish response at other operating conditions. Moreover, for a constant provided ventilation flow rate, they may cause over ventilation or insufficient ventilation when the occupancy is lower or higher than the expected maximum occupancy (consequently leads to energy waste and/or unsatisfied IAQ) [17,25]. On the other hand, due to non-stationary plant operation associated with the nonlinearity of AHU components and the coupling of the controlled variables, AHU control is a non-trivial problem [3,4].

In this paper, unlike the previous mentioned works, a comparison between two control approaches (gain scheduling and feedback linearization) applying on a nonlinear MIMO dynamic model of an AHU is investigated. Advantages and disadvantages of these methods are compared from various points of view such as achieving control objectives and energy consumption. After the state space formulation of the problem, an observer is designed to estimate state variables of the system and a regulator system is designed for disturbance rejection. Nonlinear control strategy of the system for tracking objective is developed through feedback linearization and gain scheduling approaches. Various desired commands of indoor temperature and humidity ratio (including a sequence of steps and ramps-steps) are tracked by manipulation of air and cold water flow rates.

According to results, controlled system based on feedback linearization shows more quick time responses in tracking desired set-points/paths (especially for temperature). However, using the controller designed based on gain scheduling leads to less oscillation of valves position of air and cold water (and consequently less energy consumption). It is also shown that in the presence of an arbitrary random uncertainty in model parameters, the controller designed based on feedback linearization is robust.

2. System description of the air-handling unit

A schematic view of an air-handling unit having one zone (indoor) in VAV system is shown in Fig. 1 [9]. This unit consists of supply/return fans, cooling coil, filter, ductwork, humidifier and dehumidifying coil (not shown). Since in this paper, AHU is essentially designed for operation in summer, chilled water and air loops exist. After the entrance and passing of the hot and humid air through the cooling and dehumidification coil, its temperature and humidity ratio decrease. For proper performance of the AHU, 25% of fresh air with 75% of returned air are mixed and passed through cooling unit. Finally satisfying supply air is provided and delivered to the ventilated space through output channel.

3. Dynamic modelling of the nonlinear air-handling unit

For the formulation of the problem, it is assumed that gases are ideal and mixed completely; air flow is homogeneous; the effect of air speed variations on the zone pressure is negligible and there is no air leakage except in the exhaust valves of the zone [26]. Using thermodynamics, heat and mass transfer laws, differential equations describing dynamic behaviour of the air-handling unit are determined as follows [26–28]:

$$\begin{aligned}
\dot{T}_s &= \frac{\dot{f}_a}{V_c}(T_t - T_s) + \frac{0.25\dot{f}_a}{V_c}(T_o - T_t) - \frac{\dot{f}_a h_w}{C_{pa}V_c}(0.25w_o + 0.75w_t - w_s) \\
&\quad -\dot{f}_w\left(\frac{\rho_w C_{pw}\,\Delta T_c}{\rho_a C_{pa} V_c}\right) \\
\dot{T}_t &= \frac{1}{\rho_t C_{pa} V_t}(\dot{Q}_o - h_{fg}\dot{M}_o) + \frac{\dot{f}_a h_{fg}}{C_{pa} V_t}(w_t - w_s) - \frac{\dot{f}_a}{V_t}(T_t - T_s) \\
\dot{w}_t &= \frac{\dot{M}_o}{\rho_a V_t} - \frac{\dot{f}_a}{V_t}(w_t - w_s)
\end{aligned} \tag{1}$$

where T_s/w_s, T_t/w_t and T_o/w_o are the temperature/humidity ratio of the supply air, indoor air (zone) and environment, respectively; ΔT_c is the temperature gradient in cooling unit; $\dot{f}_a$ and $\dot{f}_w$ are the air and cold water flow rates; V_c and V_t are the volume of the cold unit and indoor space (zone); $\dot{Q}_o$ and $\dot{M}_o$ are the strength of heat load and humidity load; ρ_a/C_{pa}, ρ_w/C_{pw} are the mass density/specific heat of the air and cold water. h_w and h_{fg} are the enthalpy of saturated water and vaporization (the list of thermo-fluid parameters are given in Table 1). To simplify Eq. (1), following terms are defined:

$$\begin{aligned}
&\alpha_1 = \frac{1}{V_t}, \quad \alpha_2 = \frac{1}{\rho_a V_t}, \quad \alpha_3 = \frac{1}{V_c} \\
&\beta_1 = \frac{h_{fg}}{C_{pa} V_t}, \quad \beta_2 = \frac{\rho_w C_{pw}\,\Delta T_c}{\rho_a C_{pa} V_c} \\
&\gamma_1 = \frac{1}{\rho_t C_{pa} V_t}, \quad \gamma_2 = \frac{h_w}{C_{pa} V_c}
\end{aligned} \tag{2}$$