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Research Article

Multivariable control of the bifurcation and harmonic perturbations to improve the performance of air-handling units

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ABSTRACT

In this research, nonlinear dynamics of an air-ehandling unit (AHU) is studied for tracking objectives, in the presence of harmonic perturbations. Three arbitrary realistic set-paths are considered for the indoor temperature and relative humidity. Two controllers based on feedback linearization (FBL) and pole placement approaches are designed to preserve the dynamic system around the desired tracking paths. It is shown that FBL controller works efficiently in bifurcation control and transforms the quasi-periodic limit cycles into the periodic ones (and consequently comfortable indoor conditions). In addition, FBL controller guarantees suppression of larger periodic limit cycles into the smaller ones, while it requires the lower air and cold water flow rates with less oscillatory behavior (in comparison with the pole-placement controller). However, it is observed that FBL controller fails in bifurcation control when the disturbance frequency increases. Re-tuning the dynamic gains of FBL controller is essential under such conditions.

1. Introduction

Air-conditioning systems are extensively used in commercial buildings to provide comfortable environment and acceptable indoor air quality (IAQ). Most modern buildings are equipped with energy management and control systems (EMCS) to optimize the performance of heating, ventilation and air conditioning (HVAC) systems and maintain the comfortable conditions. It is estimated that more than 50% of the building energy consumption is accounted for HVAC systems [24]. Since energy costs of buildings are directly influenced by how well an air-conditioning system performs, effective thermal management is of great importance. A comprehensive review on air-conditioning systems and control of the indoor air quality has been presented [38].

Development of accurate and simple dynamic models of HVAC systems is a key requirement for efficient EMCS design. Among HVAC components, air-handling units (AHU) are used for providing supply air with specific temperature and humidity. Finding an exact mathematical model of AHU is difficult because it has a complex nonlinear nature with multivariable parameters and time varying characteristics [35]. Several investigations have been performed for dynamic modeling and simulation of HVAC system and its components. For instance, using data acquisition system for on-line training and artificial neural network [34] and gray-box identification [10], air-handling units have been modeled. Dynamic simulation of EMCS for HVAC components [15] and simulation of a VAV air-conditioner in its cooling mode have been carried out [3]. Also, an overview of current methods used for modeling and simulation of HVAC systems has been presented [33].

Several control strategies have been presented to improve the control of energy flow and consequently the performance of AHUs. Stability analysis and tuning of PID controllers in the VAV systems [20], model based simulation and control of AHU airflow using PI controllers [37] and tuning control of a simplified VAV system have been presented [12]. Also, cascade control algorithm and gain scheduling [32], model predictive control [39] and analysis of different control schedules on EMCS of AHU have been studied [9]. Moreover, as other control approaches used for HVAC systems, rule development and adjustment of fuzzy controllers [1,14,30], optimal control [21,36,40] and adaptive self-tuning PI control [4] can be mentioned.

As the other works in the area of HVAC/AHU dynamic modeling and control, a review on air-conditioning for sleeping environments in tropics/sub-tropics [8], assessment of energy saving and decoupling for different AHU and control strategies in the hot-humid climatic region [13], dynamic energy performance analysis in study of energy efficiency retrofits of hospital buildings [5] and

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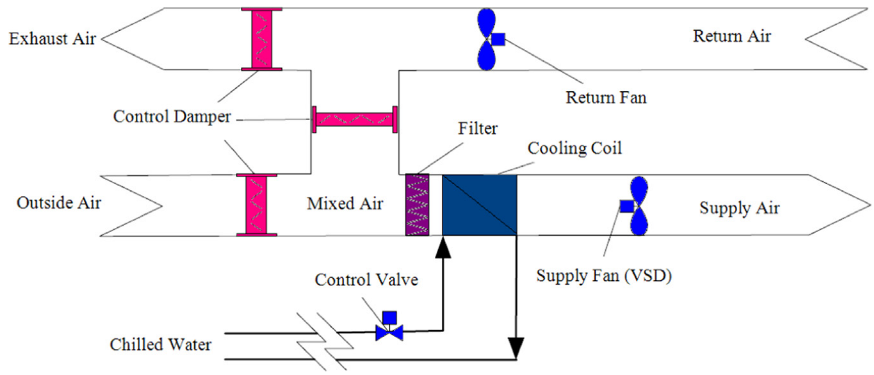

Fig. 1. Schematic view of the air-handling unit having one zone (indoor) in the VAV system.

linear algebra solution to psychometric analysis of air-conditioning systems [11] have been done.

Moreover, modeling and optimal operation of a small-scale integrated energy based district heating and cooling system [19], modeling and optimization of HVAC systems using neural network and particle-swarm algorithm [22,23], optimal order-reduced control for air conditioning system of electric vehicles [6] have been studied. Also, operating characteristics of direct-return chilled water system controlled by variable temperature difference [25] and comparison of control solutions in application of HVAC systems [26] have been investigated.

As it is observed, dynamic modeling and control of AHU have been extensively studied in the previous works without nonlinear dynamic analysis. In the presence of nonlinear sources and complex interaction of variables where the linear theories fail to predict interesting phenomena, the necessity of this analysis is more emphasized. In addition, without a prior knowledge of AHU behavior against external disturbances, applying the classical PI/PID based controllers may lead to the aggressive response of output variables and also increase in energy consumption.

Due to failure of classical controllers in the presence of nonlinearities or uncertainties, some recent investigations have been devoted to the implementation of nonlinear and robust controllers on a multivariable model of AHU [16,27,28]. In the previous researches, appropriate controllers based on gain scheduling and feedback linearization [27]; pole-placement and H_∞ control [28] were developed for disturbance rejection and tracking objectives. It should be noticed that in these works, the initial deviation of state variables from their nominal equilibrium values was considered as a simple disturbance (which is not generally a real case). This kind of perturbation does not necessarily lead to the realistic periodic solutions. To simulate the real world conditions, consideration of harmonic disturbances is beneficial because if the dynamic system behavior is recognized against them, then its behavior will be identified against any other transient disturbance. This is because any transient function can be mathematically expanded through its harmonic components via Fourier series.

Although harmonic disturbances were modeled in the previous research by Moradi et al. [29], its performance was investigated only for the regulation problem. It was studied whether the controller acts efficiently to return the system to its equilibrium points in the presence of harmonic disturbances. In this paper, unlike Moradi et al. [29], performance of two controllers are compared in tracking problem; where the system is requested to follow a desired tracking path (commanded by the occupants).

Two controllers are designed based on feedback linearization (FBL) and pole-placement methods for tracking objectives in the presence of harmonic disturbances. Three arbitrary realistic set-paths are considered for indoor temperature and relative humidity (including a sequence of steps, ramps and a combination of them). Although the control rule of the pole-placement approach is structurally simple, it cannot guarantee the appropriate performance of the system in tracking of desired set-paths. In the case of bifurcation, it is shown that FBL controller acts successfully in improving the AHU performance by converting the unstable quasi-periodic limit cycles of the indoor temperature into the periodic ones. Due to similarity and for the sake of brevity, results are not presented for the indoor humidity ratio.

In the case of large periodic limit cycles (i.e., high oscillation of indoor temperature), implementation of FBL controller results in smaller periodic limit cycles. Moreover, lower air and cold water flows with less oscillatory behavior is another benefit of FBL. However, FBL controller fails in bifurcation control for higher disturbance frequencies (a math assumption that may not occur in practice). Its gains must be re-tuned under such conditions.

2. Performance description and nonlinear dynamics of the air-handling unit

Fig. 1 shows a schematic view of an air-handling unit having one zone (indoor) in VAV system [18,27,28]. AHU is constituted of supply and return air fans, cooling coil, filter, ductwork, humidifier and dehumidifying coil (not shown). In this research, AHU is essentially designed for operation in summer; in which the chilled water loop and air loop exist. The hot and humid air has a lower temperature and humidity ratio through the cooling and dehumidification coils. A mixture of 25% of fresh air with 75% of returned air passes through the cooling unit. Finally, the desired supply air is provided and delivered to the ventilated space through the output channel.

It is assumed that gases are ideal and well mixed; 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 [2]. Using thermodynamics, heat and mass conservation, differential equations describing dynamic behavior of AHU are determined as [17,2,27,7]:

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

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 difference in the cooling unit; $\dot{f}_a$ and $\dot{f}_w$ are