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Feedback linearization based control of a variable air volume air conditioning system for cooling applications

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Abstract

Design of a nonlinear control system for a Variable Air Volume Air Conditioning (VAVAC) plant through feedback linearization is presented in this article. VAVAC systems attempt to reduce building energy consumption while maintaining the primary role of air conditioning. The temperature of the space is maintained at a constant level by establishing a balance between the cooling load generated in the space and the air supply delivered to meet the load. The dynamic model of a VAVAC plant is derived and formulated as a MIMO bilinear system. Feedback linearization is applied for decoupling and linearization of the nonlinear model. Simulation results for a laboratory scale plant are presented to demonstrate the potential of keeping comfort and maintaining energy optimal performance by this methodology. Results obtained with a conventional PI controller and a feedback linearizing controller are compared and the superiority of the proposed approach is clearly established.

Keywords: VAVAC; Feedback linearization; Nonlinear control; Air conditioning; Energy optimization

1. Introduction

Variable Air Volume Air Conditioning (VAVAC) technology is universally accepted as a means of achieving an energy efficient and comfortable environment. These are designed for reducing building energy consumption while maintaining the primary role of air conditioning. VAVAC systems are capable of supplying variable quantities of air to multiple zones to meet the requirements of the cooling load of each zone. Flow rate variation makes control of the discharge air temperature more difficult because of coupled heat and mass transfer processes taking place in the cooling coil where multiple processes simultaneously undergo changes and interact with each other. This renders control of VAVAC system quite complex as even the simplest VAVAC models are multivariable and non-linear.

Air conditioning projects in southeast Asia primarily offer a cooling only application as heating requirements are fairly nominal and subsequently this study has chosen to describe the control algorithm used in cooling only. VAV systems have become popular in hot climate zones to achieve energy efficient building design in terms of air conditioning schemes. VAVAC systems can be modeled as bilinear systems as the underlying energy balance equations contain the product of supply air flow rate which is the manipulated variable and space temperature that is commonly called the controlled variable.

Traditional PID controllers have been in use for heating, ventilating and air conditioning (HVAC) systems for a long time. Matsuba [1] carried out a parametric analysis of the stability of traditional PID controllers to avoid the hunting phenomenon using a bilinear model. House [2] developed an optimal control strategy which determines the minimum operating cost for the system to achieve a desired comfort level. The governing equations were derived by applying the principles of conservation of mass and energy. A quadratic cost function in terms of the components of HVAC was formulated on the basis of energy usages and the same was minimized. Semsar [3] formulated a bilinear model of a HVAC system and presented a design of reduced order state and thermal load observer based on the model. Serrano [4] designed a nonlinear disturbance rejection controller using Lyapunov stability theory for bilinear model of VAVAC

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Nomenclature

C_p	specific heat at constant pressure (J/kg K)
C_v	specific heat at constant volume (J/kg K)
D	diameter of duct (m)
E	Error
h_{fg}	latent heat of water (J/kg)
M	heat mass capacitance
N	fan speed (rpm)
Q	volumetric flow rate (m^3/s)
T	temperature (°C)
U	overall heat transfer coefficient (W/m^2 K)
V	volume (m^3)
W	humidity ratio (kg_w/kg_a)

Greek Letters

χ	duty cycle of compressor
ρ	air density (kg/m^3)
κ	moisture load

Subscripts

a	air
ai	input air
ao	output air
amb	ambient
cc	cooling coil
d	duct
i	index
sd	supply duct
ss	steady state
tc	test cell
t	tank
w	water

systems. Zaheeruddin [5] designed the so-called *preview* controllers based on the prediction of incoming disturbances. A decentralized preview controller was designed for a multizone space heating system. Preview temperatures were approximated by a series of step functions. Zaheeruddin et al. [6] developed a transient model and then designed a decentralized controller with linear and nonlinear models based on the optimization of quadratic performance criteria. Zaheeruddin and Patel [7] designed an optimal control law based on a reduced order model, which was then implemented on a full order nonlinear system. Zaheeruddin [8] proposed a dynamic model suitable for multizone VAV systems and recently Thosar et al. [9] reported energy optimization of a VAVAC system employing a genetic algorithm. Calvino [10] presented an application of an adaptive fuzzy controller that does not require modeling of outdoor and indoor environment. Anderson [11] presented a typical hot water to air heating system.

Most of the research work mentioned above is based on a linearized mathematical model of the HVAC system and the controller design is based on linear quadratic regulator theory or traditional PID controllers. The objective of this study is to develop a control system which can compensate for nonlinearity of the plant. This is achieved through feedback linearization in contrast to the usual "linearization around an operating point" approach. This enables us to design a controller which ensures global stability with the desired performance at all operating points of the system. In this study we present the applicability of a feedback linearization based nonlinear controller to complex nonlinear VAV systems. Control of nonminimum phase multivariable, nonlinear and nonlinearizable plant with coupling of variables is indeed a challenging task from a control viewpoint. The controller presented here possesses excellent tracking of set point and speed and is adaptive to changes in its surroundings. Comparison with a PI controller is only meant to signify the extent of the achievement and does not imply that other techniques cannot perform suitably.

2. Brief description of the VAVAC system

The VAVAC system considered (Fig. 1) in this study consists of two zones comprising one test cell each. The instrumentation scheme consists of a number of sensors for measurement of temperature, pressure, humidity and flow at various locations. A computer interfaced data acquisition and control system, using real time software, provides a platform to study the effect of different control strategies. The major components of the system are: chiller, cooling coil, fan, supply and return ducts, VAV boxes and storage tank. The cooling coil is typically a counter cross flow type. The chilled water tank is the link between the chiller and the cooling coil with a 3-way valve determining the amount of water going through the cooling coil. The air flow rate to the zone is controlled through fan speed control and by changing the damper position. The chilled water mass flow rate is controlled by a 3-way valve as well. Air flow rate and temperature of air supplied are two control inputs which can be changed simultaneously in the two cells.

3. State space modeling

The design of controllers for a VAVAC system, nonlinear and multivariable in nature, requires the knowledge of accurate dynamic models of the system. The major focus in modeling is on the dynamics of the air handling unit (AHU) and each zone with the AHU involving dynamics of the fan, heat and mass transfer in the cooling coil and the air distribution system. Each of these components has been modeled based on lumped capacity considerations employing fundamental conservation equations of mass and energy with the following assumptions:

1. Humidity and indoor air quality are not controlled.
2. Transient and spatial effects are neglected for the air in each component.
3. Heat transfer at the interior and exterior surface of a zone, supply ducts, return ducts, etc., are modeled using constant heat transfer coefficients.
4. Axial mixing of water is neglected and the water temperature is assumed to be constant across a given cross section.