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On-line adaptive control of a direct expansion air conditioning system using artificial neural network

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HIGHLIGHTS

- ► We develop an ANN-based on-line adaptive controller for a DX A/C system.
- ► It addressed limited controllable range for an earlier ANN-based controller.
- ► The controller was validated experimentally by controllability tests.
- ► The controller could work well within the entire range of operating conditions.

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ABSTRACT

A common issue to all controllers, including the previously developed artificial neural network (ANN)-based controller for a direct expansion (DX) air conditioning (A/C) system, developed based on system identification is limited controllable range. To address the issue, an ANN-based on-line adaptive controller has been developed and is reported. The ANN-based on-line adaptive controller was able to control indoor air temperature and humidity simultaneously within the entire expected controllable range by varying compressor and supply fan speeds. The controllability tests for the controller were carried out using an experimental DX A/C system. The test results showed the high control accuracy of the ANN-based on-line adaptive controller developed, within the entire range of operating conditions. It was able to control indoor air dry-bulb and wet-bulb temperatures both near and away from the operating condition at which an ANN-based dynamic model in the ANN-based on-line adaptive controller was initially trained.

1. Introduction

Direct expansion (DX) air conditioning (A/C) systems have been increasingly used over the recent decades in buildings, especially in small to medium scaled buildings. Compared to central chilled water-based A/C systems, DX A/C systems are more energy efficient and more flexible in installation, but cost less to own and maintain. Conventional DX A/C systems equipped with single speed compressor and fan rely on on–off cycling of compressor to maintain only the indoor dry-bulb temperature, leading to either space overcooling or uncontrolled equilibrium indoor air humidity. Consequently, a reduced level of thermal comfort for occupants and low energy efficiency will be resulted in [1,2]. With the advancement of variable speed drive technology, it becomes possible for DX A/C units to have the speeds of their compressors and supply fans varied to achieve simultaneous control over both indoor air temperature and relative humidity (RH) [3].

Various control strategies aiming at simultaneously controlling indoor air temperature and humidity have been designed for, and employed in DX A/C systems. These include the traditional PI or PID control strategies. An experimental investigation by Krakow et al. [4] indicated that to maintain indoor air temperature by varying compressor speed, and indoor RH by varying supply fan speed, separately, using a PID control method, space air temperature and RH may be controlled simultaneously. However, the transient performance of the two decoupled feedback loops was inherently poor due to the strong cross-coupling between the two feedback loops [4,5].

In order to address the coupling effect, other advanced physical-based control strategies have been developed. Li and Deng [6,7] developed a novel direct digital control (DDC)-based capacity controller for a variable speed DX A/C system to control indoor air temperature and humidity simultaneously. However, using this steady-state control strategy, it would take time for the controller to

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Nomenclature

J	Jacobian of the system (−)
k	counter of control action by the ANN-based on-line adaptive controller (−)
l	number of data sets used for on-line training the ANN-based dynamic model ($l = 10$ in the current study) (−)
P_C	percentage of the maximum compressor speed (%)
P_F	percentage of the maximum supply fan speed (%)
q	time delay operator (−)
$\mathbf{r}$	control reference (°C)
τ	time duration starting from the beginning of control to the current time instant
t	time instant (where t is the present time step, $(t - 1)$, the time instant at last time step and $(t + 1)$, the time instant at next time step, and the time interval between time instant t and $(t + 1)$ is Δt) (−)
Δt	time interval between two consecutive control actions by the ANN-based on-line adaptive controller
T	indoor air temperature (°C)
$\mathbf{u}$	inputs to a system (−)
$\mathbf{U}$	data of indoor air dry-bulb and wet-bulb temperatures collected for on-line training of ANN-based dynamic model
$\mathbf{y}$	outputs from a system (−)
$\mathbf{Y}$	data of compressor and supply fan speeds collected for on-line training of ANN-based dynamic model

Subscripts and superscripts

db	dry-bulb temperature
m	ANN-based dynamic model
wb	wet-bulb temperature
p	values of the variables collected at a time

Abbreviations

A/C	air conditioning
ANN	artificial neural network
DDC	direct digital control
DIC	direct inverse control
DX	direct expansion
LGU	load generating unit
MIMO	multi-input multi-output
RH	relative humidity

obtain the information required if the space cooling load was changed, leading to an unacceptable control sensitivity. In addition, Qi and Deng [8] developed a multi-input multi-output (MIMO) control strategy for simultaneously controlling the indoor air temperature and humidity by regulating the speeds of compressor and supply fan in an experimental DX A/C system. This MIMO controller was developed based on a physical model and took into account the coupling effects among multiple variables of the DX A/C system [5]. However, it can only perform as expected near the operating point where the model governing equations were linearized.

Therefore, it has been challenging to control indoor air temperature and humidity simultaneously using a DX A/C system, because of the complexity of the DX A/C system as reflected by its nonlinearity, MIMO characteristic and coupled sub-systems which influenced one another [9,10].

On the other hand, ANN has been proven to be a useful tool in modeling the dynamic operating performance of a nonlinear multivariable system, such as a DX A/C system. This is because it has been shown that ANN has a powerful ability in recognizing accurately the inherent relationship between any set of inputs and outputs without requiring a physical model. This ability is essentially independent of the system complexity such as nonlinearity, multiple variables, coupling, with noise and uncertainty [11–16]. An ANN-based control strategy which could deal with a nonlinear MIMO complex system based on an ANN-based model can then be developed. As an intelligent nonlinear dynamic control method, an ANN-based control strategy offers a viable solution to the control over complex systems [17–23].

Therefore, ANN was chosen to model and control a DX A/C system as previously reported [24,25], where both an ANN-based steady-state model and an ANN-based dynamic model, and an ANN-based controller were developed. This ANN-based controller developed was composed of the ANN-based dynamic model, which was off-line trained beforehand and remained unchanged during control, and an ANN-based inverse model, which was updated during control to minimize the difference between control references and controlled variables. However, similar to all models developed through system identification, the ANN-based dynamic model used was off-line trained using the operating data at a particular point, or the training point. It would therefore fail to simulate system performance when the operating conditions drifted away from the training point, making the ANN-based inverse model incapable of being updated to correctly trace the control references. Therefore, the ANN-based controller can only work as expected near the system operating point at which the ANN-based dynamic model was off-line trained. In order to make the ANN-based controller workable at the entire operation range of the DX A/C system, the concept of adaptive control was applied to the ANN-based controller developed to turn it into an ANN-based on-line adaptive controller. In this ANN-based on-line adaptive controller, an ANN-based dynamic model was trained on-line using the data collected and thus updated on a regular basis as the system operation went on. Consequently the model can represent the real-time dynamic operating performance of the DX A/C system. Then the ANN-based inverse model could be updated correctly to adapt to the change in operating conditions.

This paper reports on the detailed development of the ANN-based on-line adaptive controller and the results of its controllability tests. Firstly, the ANN-based controller previously developed for a DX A/C system [25] is briefly reviewed, and the development of the ANN-based on-line adaptive controller detailed. Secondly, the results of controllability tests for the ANN-based on-line adaptive controller including initial start-up stage test, command following test, disturbance rejection test and commanding following with disturbances test using an experimental DX A/C system are presented.

2. ANN-based on-line adaptive controller development for the experimental DX A/C system

2.1. The ANN-based controller previously developed

The details of the ANN-based controller previously developed were reported elsewhere [25]. For the completeness of the current paper, these are briefly reproduced as follows:

When developing the ANN-based controller, the direct inverse control (DIC) strategy following the ANN-based direct design method [20] was used. The controller included an ANN-based dynamic model and an ANN-based inverse model for the experimental DX A/C system. The ANN-based inverse model, as opposed