Building and Environment 49 (2012) 141–153

Contents lists available at SciVerse ScienceDirect

Building and Environment

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

RLF and TS fuzzy model identification of indoor thermal comfort based on PMV/PPD

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ARTICLE INFO

Article history:
Received 20 July 2011
Received in revised form
6 September 2011
Accepted 9 September 2011

Keywords:
Thermal comfort
Building model
HVAC
PMV/PPD
RLF method
Energy control

ABSTRACT

This work presents a hybrid model to be used for effectively controlling indoor thermal comfort in a heating, ventilating and air conditioning (HVAC) system. The first modeling part is related to the building structure and its fixture. Since building models contain many nonlinearities and have large thermal inertia and high delay time, empirical calculations based on the residential load factor (RLF) is adopted to represent the model. The second part is associated with the indoor thermal comfort itself. To evaluate indoor thermal comfort situations, predicted mean vote (PMV) and predicted percentage of dissatisfaction (PPD) indicators were used. This modeling part is represented as a fuzzy PMV/PPD model which is regarded as a white-box model. This modeling is achieved using a Takagi-Sugeno (TS) fuzzy model and tuned by Gauss-Newton method for nonlinear regression (GNMNR) algorithm. The main reason for combining the two models is to obtain a proper reference signal for the HVAC system. Unlike the widely used temperature reference signal, the proposed reference signal resulting from this work is closely related to thermal sensation comfort; Temperature is one of the factors affecting the thermal comfort but is not the main measure, and therefore, it is insignificant to control thermal comfort when the temperature is used as the reference for the HVAC system. The overall proposed model is tested on a wide range of parameter variation. The corresponding results show that a good modeling capability is achieved without employing any complicated optimization procedures for structure identification with the TS model.

1. Introduction

Cooling and heating loads are different from one building to the other depending on the structure and dedication of the building. There are also differences in building structures from place to place because of different climates and weather harshness. These differences will correspondingly affect thermal inertia and introduce dead time and nonlinearities in the indoor response due to outdoor environment change [1]. These quantities cannot be easily and precisely represented by applied physical laws and obtain an explicit model of a building [2]. Therefore, empirical methods are used to exemplify the indoor behavior concerning outside effects. This work adopts the residential load factor (RLF) empirical method in deriving heat and humidity transfer equation for a building structure with all its variable thermal inertia, dead time and nonlinearities. The RLF has been adopted widely by many researchers to calculate cooling and heating loads, see [3–5] for an example. The motive for using RLF extensively is to able share many of its features in a computational process. The RLF method is superior to all other methods as they ignore solar and internal gains and are based on summing surface heat losses, infiltration losses, ventilation losses, and distribution losses [6]. The earlier residential load calculation methods have been published by the Air Conditioning Contractors of America (ACCA) in 1986, [7]. After that, the ASHRAE Handbook Fundamentals include a method based on 342-RP (McQuiston1984), [8]. Furthermore, RLF is appropriate for variable air volume (VAV) systems. The VAV approach reduces cooling air flow into a room via constant air volume (CAV) and thermostat control feedback, [9].

The primary purpose of HVAC systems is to control the indoor temperature and relative humidity (output of the building model) since they are the major factors affecting the comfort of the building's occupants. There are many criteria used to determine the degree of the thermal comfort index; such as wet bulb temperature

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doi:10.1016/j.buildenv.2011.09.012

(T_w) [10], effective temperature (ET) [11], operative temperature (OpT) [12], thermal acceptance ratio (TAR) [13], wet bulb dry temperature (WBDT) [14], and so on. However, the major widely used thermal comfort index is the predicted mean vote (PMV) index. The PMV model is developed by Fanger in 1972, [15]. Based on this model, a person is said to be in thermal comfort based on three parameters: 1. the body is in heat balance; 2. sweat rate is within comfort limits; and 3. mean skin temperature is within comfort limits, [16]. Based on these parameters, Fanger established his empirical model by using the estimation of the expected average vote of a panel of evaluators. The process of obtaining PMV value from Fanger's model require a long time since the number of input variables takes a long routine of calculations and some need iteration. For the iteration computation, if the initial guess of the input variables is far from the root, it might take a long computation time to converge to the root. The Fanger's model has been used directly by using a spreadsheet or numerical methods to obtain a thermal comfort index [17–19], while others converted it into a black-box model [20–22]. In this paper, the Fanger's model is converted into a white-box, which is useful for analytical processes.

The PMV is also used to predict the number of people likely to feel uncomfortable as a cooling or warming feeling. This feeling is sited under the category of the Predicted Percentage of Dissatisfied (PPD) index. The output of PPD is classified into two categories, comfortable and uncomfortable, according to human being sensation. The variation behavior of PPD versus PMV is imperative for the HVAC system to control indoor desired conditions as implemented by many researchers [23–28]. In this paper, the PPD is represented by a Takagi-Sugeno (TS) fuzzy model derived using a training data set from Fanger's model. The parameters of the TS model are tuned by the Gauss-Newton method for nonlinear regression (GNMNR) algorithm. The Gauss-Newton method is an algorithm for minimizing the sum of the squares of the residuals between data and nonlinear equations. The key concept underlying the technique is that a Taylor series expansion is used to express the original nonlinear system in an approximate linear form. Then, least-squares theory can be used to obtain new estimates of parameters that move in the direction of minimizing the residual, [29].

The improvement of the PPD model by using the TS GNMNR tuned fuzzy model is due to the use of the clustering concept of the learning data set. This significantly reduces the number of rules and number of iterations and provides small margin error when compared with neuro-fuzzy model tuned using the back-propagation algorithm [30] with its notorious long training time requirement [31]. The margin of errors for TS model are less than those of other methods such as neural networks, feed forward neural network and the least square methods [19–21]. On the other hand, TS model is a white-box model which is useful for analytical processes such as prediction and extrapolation beyond a given training data set by using parameters layers. In addition, adding the TS model to the building model provides flexibility to control coupled variables like temperature and relative humidity. In this way, the controller can easily track the desired thermal sensation for the conditioned space by controlling more controllable variables like the indoor air velocity and the flow rate of the fresh air.

2. Methodology

The framework in this paper is to build a model of the building and a model of the thermal comfort both separately then combine them to form a sole unit. The software that is used to perform all identification processes and simulation is Matlab and its toolboxes; system identification and control system toolboxes were used to identify and build the model while fuzzy logic toolbox was used for the TS model identification. The obtained models are then introduced in Matlab/Simulink environment for simulation and analysis. The integrated model is followed by these steps:

2.1. Building model

The proposed building model was structured in four groups, which represented four building domains: conditioned space, opaque surfaces structure, transparent fenestration surfaces and slabs.

The first group, *conditioned space sub-model*, is related to the thermal capacitance of indoor air space and building furniture, where air space and furniture are considered at same temperatures. The second group, *opaque surfaces' structure sub-model*, is related to the radiation exchanges between the envelope and its neighborhood and to the heat and mass transfers through the opaque surfaces' structure material. The opaque surfaces at a building structure are comprised of walls, doors, roofs and ceilings. The third group, *transparent fenestration surface's sub-model*, is related to the direct and indirect radiation exchanges between the transparent envelope and its neighborhood and to the heat transfers through the transparent fenestration surfaces at a material. The transparent fenestration surfaces are comprised of windows, skylights and glazed doors. The fourth group, *slab floors' sub-model,* is related to the heat transfers through the slab floor layers due to heat release and store in it. These four factors are the main factors associated with the heat gain/losses to/from building structure as a result of outdoor temperature and solar radiation. Furthermore, these factors create a load leveling or flywheel effect on the instantaneous load for the building model.

The building model is developed to determine the optimal response for the indoor temperature and humidity ratio by taking temperature and moisture transmission based on the RLF empirical methods. The main objective of this model approach is to get a relationship between indoor and outdoor variation data like the temperature and humidity ratio. With the RLF approach, the subsystem method treats outdoor air temperature and humidity ratio as independent variables in the analysis. The subsystems are as follows:

2.1.1. Opaque surfaces

The heat balances of Opaque surface as following the law of conservation of energy can be written as:

$$M_{wl}cp_{wl}\frac{dt_{wl,t}}{dt} = \sum_i \dot{Q}_{in} - \sum_i \dot{Q}_{out} \quad (1)$$

where $\sum \dot{Q}_{in}$ and $\sum \dot{Q}_{out}$ are the heat gain and loss through walls, ceilings,^{i} and doors^i (W), $M_{wl}cp_{wl}$ is the heat capacitance of walls, ceilings, and doors (J/K).

By applying RLF method on Eq. (1) to get transfer function as follow:

$$T_{wl_{in}}(s) = \begin{bmatrix} G_{1,1} & G_{1,2} & G_{1,3} \end{bmatrix} \begin{bmatrix} T_o(s) \\ k_2 \\ T_r(s) \end{bmatrix} \quad (2)$$

where $G_{1,11} = k_1/(\tau_5 s+1)$, $G_{1,12} = 1/(\tau_5 s+1)$, $G_{1,13} = k_3/(\tau_5 s+1)$, $\tau_5 = M_{wl}cp_{wl}/\sum_j A_{w_j}U_jOF_t + \sum_j A_{w_j}h_{i_j}$, $k_1 = \sum_j A_{w_j}U_jOF_t/\sum_j A_{w_j}U_j OF_t + \sum_j A_{w_j}h_{i_j}$ (function of thermal resistant and outside temperature), $k_2 = \sum_j A_{w_j}U_jOF_b + \sum_j A_{w_j}U_jOF_rDR/\sum_j A_{w_j}U_jOF_t + \sum_j A_{w_j}h_{i_j}$, (function of thermal resistant and solar radiation incident on the surfaces) (°C), $k_3 = \sum_j A_{w_j}h_{i_j}/\sum_j A_{w_j}U_jOF_t + \sum_j A_{w_j}h_{i_j}$, (function of thermal resistant and convection heat transfer), A_w = net surface area (m^2), F = surface cooling factor (W/m^2), U = construction U-factor (W/(m^{2}K)), OF_t, OF_b, OF_r = opaque-surface cooling factors, and DR = cooling daily range (K).