Dynamic indoor thermal comfort model identification based on neural computing PMV index

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Abstract. This paper focuses on modelling and simulation of building dynamic thermal comfort control for non-linear HVAC system. Thermal comfort in general refers to temperature and also humidity. However in reality, temperature or humidity is just one of the factors affecting the thermal comfort but not the main measures. Besides, as HVAC control system has the characteristic of time delay, large inertia, and highly nonlinear behaviour, it is difficult to determine the thermal comfort sensation accurately if we use traditional Fanger’s PMV index. Hence, Artificial Neural Network (ANN) has been introduced due to its ability to approximate any nonlinear mapping. Using ANN to train, we can get the input-output mapping of HVAC control system or in other word; we can propose a practical approach to identify thermal comfort of a building.

1. Introduction
Thermal comfort can be defined as the state of mind which expresses satisfaction with the thermal environment, and therefore it depends on the individual’s physiology and psychology [1]. As each building presents its own constructional characteristics and occupant’s habit, most common HVAC systems are incapable of providing thermal comfort by taking into account these variations, further increasing energy consumptions. To solve the problems, selection of suitable control system such as neural computing Predictive Mean Vote (PMV) indices is important to consider the indoor ambiences and occupants’ habits to achieve optimal thermal comfort, hence minimize the percentage of dissatisfaction and subsequently reduce energy consumption.

HVAC control system has the characteristic of time delay, large inertia, and highly nonlinear behaviour, making it is difficult to determine the thermal comfort sensation accurately if we use traditional Fanger’s PMV index [2]. Hence, in this paper, Artificial Neural Network (ANN) has been introduced due to its ability to approximate any nonlinear mapping. Using ANN to train, we can get the input-output mapping of HVAC control system or in other word; we can propose a practical approach to identify thermal comfort of a building.

2. Modelling Approach
PMV indices are adopted in this paper. In the calculation, six variables were taken into consideration: two personal dependant variables which are clothing insulation and occupant’s activity level; four environmental dependent variables which are air temperature, air humidity, mean radiant temperature,
and air velocity. Based on these, the following equations were derived for dynamic thermal comfort sensation model:

\[ M_u c_p H \frac{dT_{sk, t}}{dt} = M - W \mp R \mp C \mp K - E - RES \]  \hspace{1cm} (1)

\[ M_u c_p H \frac{dT_{sk, t}}{dt} = (M - W) - \left\{ 3.9 f_{cl} (t_{cl} - \overline{t_r}) \right\} - \left\{ f_{cl} \times (12.1 \sqrt{V_{ar}}) \times (t_{cl} - t_a) \right\} - \left\{ (3.05 \times 10^{-3})(256 T_{sk, t} - 3373 - p_a) + 0.42 [M - W - 58.15] \right\} - \left\{ 0.0014M (34 - t_a) + (1.72 \times 10^{-5})(M)(5867 - p_a) \right\} \]  \hspace{1cm} (2)

\[ t_{cl} = T_{sk, t} - y \]  \hspace{1cm} (3)

\[ y = 3.96 \times 10^{-8} f_{cl} l_{cl} \left[ (t_{cl} + 273)^4 - (\overline{t_r} + 273)^4 \right] + 2.38 f_{cl} l_{cl} (t_{cl} - t_a)^{1.25} \]  \hspace{1cm} (4)

Substitute (3) into (2) yields:

\[ M_u c_p H \frac{dT_{sk, t}}{dt} = (M - W) - \left\{ 3.9 f_{cl} (T_{sk, t} - y - \overline{t_r}) \right\} - 12.1 f_{cl} \sqrt{V_{ar}} (T_{sk, t} - y - t_a) - \left\{ (3.05 \times 10^{-3})(256 T_{sk, t} - 3373 - p_a) + 0.42 [M - W - 58.15] \right\} - \left\{ 0.0014M (34 - t_a) + (1.72 \times 10^{-5})(M)(5867 - p_a) \right\} \]  \hspace{1cm} (5)

Taking Laplace Transform with zero initial condition:

\[ M_u c_p H S T_{sk} (s) = (M - W) - \left\{ 3.9 f_{cl} (T_{sk} (s) - y - \overline{t_r}) \right\} - 12.1 f_{cl} \sqrt{V_{ar}} (T_{sk} (s) - y - t_a) - \left\{ (3.05 \times 10^{-3})(256 T_{sk} (s) - 3373 - p_a) + 0.42 [M - W - 58.15] \right\} - \left\{ 0.0014M (34 - t_a) + (1.72 \times 10^{-5})(M)(5867 - p_a) \right\} \]  \hspace{1cm} (6)

Collect the \( T_{sk} \) to the left hand side of (6) and rearrange:

\[ M_u c_p H S T_{sk} (s) + 3.9 f_{cl} T_{sk} (s) + 12.1 f_{cl} \sqrt{V_{ar}} T_{sk} (s) + 0.781 T_{sk} (s) = L \]  \hspace{1cm} (7)

\[ \left[ 3.9 f_{cl} + 12.1 f_{cl} \sqrt{V_{ar}} + 0.781 \right] T_{sk} (s) \left( \frac{M_u c_p H}{3.9 f_{cl} + 12.1 f_{cl} \sqrt{V_{ar}} + 0.781} \right) S + 1 \right] = L \]  \hspace{1cm} (8)

\[ XT_{sk} (s) \left( \frac{M_u c_p H}{X} \right) S + 1 \right] = L \]  \hspace{1cm} (9)

\[ PMV (s) = \left( \frac{L}{L_S + 1} \right) \left( \frac{1}{X} \right) \]  \hspace{1cm} (10)

where
\[
\tau = \frac{M_h c_p_h}{X}
\] 
(11)

\[
X = 3.9 f_{cl} + 12.1 f_{cl} \sqrt{V_{ar}} + 0.781
\] 
(12)

\[
L = (M - W) + (y + t_r) + 12.1 f_{cl} \sqrt{V_{ar}} (y + t_a) - \left( \frac{y}{0.155 f_{cl}} \right) + 3.05 \times 10^{-3} (3373 + p_a) + 0.42 [58.15 - (M - W)] + 0.0014 M (t_a - 34) + (1.7 \times 10^{-5}) M (p_a - 5867)
\] 
(13)

where \( S \) is heat rate storage in a body, \( M \) is metabolism, \( W \) is External work, \( R \) is heat exchange by radiation, \( C \) is heat exchange by convection, \( K \) is heat exchange by conduction, \( E \) is heat loss by evaporation, \( RES \) is heat exchange by respiration, \( M_h \) is mass of human body in (kg), \( c_p_h \) is specific heat of human body in (J/kg.˚C), \( T_{sk,t} \) is skin’s temperature at time \( t \) in (˚C), \( t_{cl} \) is surface temperature of clothing in (˚C), \( f_{cl} \) is ratio of the surface area of the clothed body to surface area of nude body and \( p_a \) is water vapor pressure in (kPa).

It is noted that the value of \( t_{cl} \) in equation (3) is to be calculated iteratively in finding the roots of nonlinear equation. A first guessed value of \( t_{cl} \) will be introduced to the second member in equation (3). If the initial guess value of \( t_{cl} \) is far from root, it will consume a long time to converge to the root. Therefore, the initial guessed value in this research was taken by averaging the air temperature \( t_a \) and skin temperature \( T_{sk} \).

To make sure the equation used for each term in the transient heat balance equation correct or not, sample input will be supplied and heat transfer for each term has to be calculated out and the result has to be validated using the excel spread sheet of ISO 7730 PMV calculator [3]. Based on comparison between manual calculations and values obtained using ISO 7730 PMV calculator, it can be shown that heat transfer for each term in equation (1) is quite similar for both approaches. Hence, the equations are validated and can be used for model derivation.

3. Application of Artificial Neural Network (ANN)

From equations (1) to (13), we can observe that the PMV value calculation is very complicated if using manual calculation. In addition, the determination of \( t_{cl} \) value using equation (6) may take long computing time due to iterative native of the equation and hence it is not practical to determine PMV value in real time application. In order to solve this problem, a nonlinear identification model, Artificial Neural Network (ANN) is introduced to approximate nonlinear relationship between input and output value.

Since PMV value is affected most by the six thermal variables; indoor air temperature, mean radiant temperature, indoor air humidity, human metabolism, air velocity, and thermal clothing insulation, therefore the input layer dimension chosen is 6-dimensional. For output layer, there is only one PMV value hence the dimension for output layer chosen is one-dimensional. 3 hidden layers are used to reduce the complexity of calculation. To ensure the output is not fall into the flat area at the beginning of study, the initial weight values are randomly generated, and the values are relatively small so that each neuron can learns from the biggest change in the local activation function. Learning rate of 0.10 is selected for this research.

4. Simulation Results

All simulations are conducted using our previous building model in Matlab environment [4]. Figure 1 (a) shows the graph of dynamic PMV thermal comfort value against 43000 samples data. As can be seen from the graph, the black colour curve is the model or dynamic PMV output while the red colour curve is the plant or neural network model output. The result from this graph showed that neural network can learn well or mimic dynamic PMV thermal comfort since both the curves are quite similar. Based on the specified minimum desired error of 0.0001, the network training achieved the desired goal error at epochs
The derived dynamic PMV equation was then validated by comparing the trained dynamic neural computing PMV index with TS-Fuzzy Logic model as shown in Figure 1 (b). The result showed that human thermal comfort evaluation model established in this paper agreed well with existing research results, and may directly be used in future research work.

Figure 1 (c) shows the result from practical approach of PMV thermal comfort identification using Artificial Neural Network, the training and validation data. The dashed lines in each graph indicate the perfect result. The correlation coefficient R value is an indication of the relationship between outputs and targets. The R value of training and validation are 0.99969 and 0.99971 respectively. This indicates that there is an exact linear relationship between outputs and targets. It can be said that for this simulation, the overall performance indicates a good fit.

5. Conclusion
The results proved that human thermal comfort evaluation model established in this paper agreed well with existing research results, and may directly be used in future research work. Results also show that the proposed ANN method can track down the desired PMV thermal comfort for a specified condition space.

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