Operating Performance Simulation of Auto-tuning Feed-forward in Temperature Control of Hydronic Heating System in Residential Building

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Abstract

In many temperature control systems for rooms, proportional-integral control is often used and a temperature setback is well applied. Applying a feed-forward is promising to improve its target response whereas its proper setting is required. In this paper, a two-degree of freedom control combining auto-tuning feed-forward and feedback was suggested for the control strategy. Simulation was then used to evaluate its performance compared to three conventional control strategies. Simulation results showed the two-degree of freedom control improved followability to the change of a target value by 30% compared to the proportional-integral control. In conclusion, room temperature control is able to be improved by simple way without initial nor periodical tuning by service engineers.

Introduction

In Europe, hydronic heating systems are widely introduced in residential buildings. To keep room temperature at set points, water temperature and the systems are controlled. In most temperature control systems for rooms, the following three strategies are often used; an on/off switching controller with a constant water temperature (CWT), heating curve (HC), and feedback (FB) controller i.e. Proportional-integral (PI) controller. The HC is a static feed-forward (FF) control with ambient temperature as input. However, water temperatures of CWT and HC tend to be set high to avoid under heating. It causes unnecessary system on/off. On the other hand, FB has a problem in a target response even though a temperature setback is well used especially during night.

A wide range of literature exists on advanced control strategies utilising techniques such as: model predictive control (MPC) (Karlsson (2011), Kummert (2000) and Chen (2002)); neural network based control (Ferreira (2012), Yang (2003) and Arigiriou (2004)); and agent-based control (Joumaa (2011) and Ramchum (2011)). However, while the technologies present promising results in theory, they are quite complex to implement in practice due to the required effort for model development, computation and specialist knowledge. To improve temperature control performance with simple and effective way, applying a FF to FB is one of promising measures.

Thomas (2005) investigated the advantages of using FF with FB in temperature control of buildings. In particular, the performances of using FF from internal disturbances were evaluated by simulation although the simulations were carried out only with several constant outdoor temperatures and a constant set room temperature. Huchtemann (2013) studied an adaptive supply temperature control. In this study, two HCs were applied for daytime and night-time to compensate set room temperature differences. In real practice, the HCs have to be properly set by installers or end-users to make them work well.

Therefore, the authors suggest a two-degree of freedom control (2DOF) combining auto-tuning FF to compensate ambient temperature and set room temperature changes with FB for the control strategy. By adapting a simple auto-tuning function, it does not require initial nor periodical tuning by service engineers without increasing computational complexity. In this paper, the operating performance of this 2DOF approach was evaluated by simulation compared to other conventional controls i.e. CWT, HC and FB under two temperature settings; constant room temperature setting and night setback room temperature setting.

Supply water temperature control

The functional diagram of the 2DOF is shown in Figure 1. Supply water temperature is decided by the basic supply water temperature and output from the FB. The FF decides the basic supply water temperature T_{water}

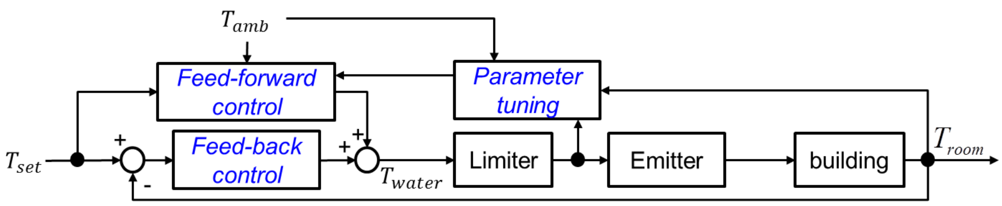

Figure 1: Functional diagram of auto-tuning feed-forward control and feedback control.

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Table 1: Wall, roof and window construction.

Building element	Material	Thickness	Conductivity	Density	Specific heat	U-value
		m	W/(m K)	kg/m^3	J/(kg K)	W/(m^2 K)
External wall	Brick	0.350	0.75	1300	840	1.40
	Plaster	0.040	0.51	1120	960	
Internal wall	Plasterboard	0.020	0.17	800	1090	1.52
Roof (horizontal base of roof space)	Insulation (Mineral wool)	0.035	0.051	290	800	1.00
	Plasterboard	0.010	0.17	800	1090	
Roof tiles	Tiles	0.026	1.3	2000	840	5.27
Ground floor	Plywood	0.010	0.15	700	1420	0.86
	Insulation (Mineral wool)	0.043	0.051	290	800	
	Concrete	0.100	1.3	2000	840	
First floor	Plywood	0.020	0.15	700	1420	2.54
Window	Double glazed	-	-	-	-	2.95

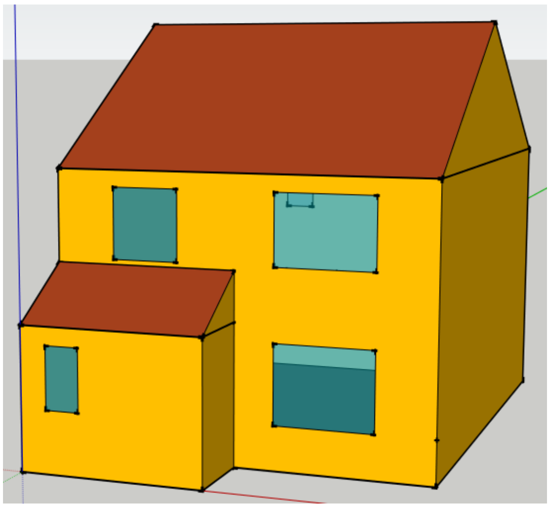

Figure 2: Modelled house.

from coefficients α and β and temperature difference between set room temperature T_{set} and ambient temperature T_{amb} as in (1).

$$T_{water} = \alpha(T_{set} - T_{amb}) + \beta \quad (1)$$

The coefficient α, which is a combined coefficient of building heat loss coefficient and emitter (radiator) heat supply characteristic, is auto-tuned with operating data including the supply water temperature, the ambient temperature and room temperature T_{room} as in (2). N is sampling size which is expected to be equivalent to a day by taking cycles of outdoor temperature and occupant behaviour into consideration.

$$\alpha = \frac{N-1}{N}\alpha + \frac{1}{N}\frac{T_{water} - \beta}{T_{room} - T_{amb}} \quad (2)$$

PI controller is used for FB and its equation is as shown in (3). The controller's output at time t $u(t)$ is calculated by the gain K, the integral time T_i and the error value at time t $e(t)$.

$$u(t) = Ke(t) + \frac{K}{T_i}\int e(t)dt \quad (3)$$

Operating performance simulation

The operating performance of the 2DOF was evaluated based on a simulation comparison to CWT, HC and the FB. The simulation model was developed on TRNSYS and consists of a single-zone building, a radiator and a room temperature controller. The existing modules in TRNSYS are used except for the auto-tuning FF control that was created by the authors.

Modelled house

A typical UK house as shown in Figure 2 was modelled by using TRNSYS. The house is a detached house with a south-facing orientation, and having windows toward south and north. The window ratio toward the external wall is 6%. In this study, inside of the house was modelled as a single zone as a simplification. The settings Marshall (2011) described were used in the following modelling variable. The wall, roof and window construction used in model are shown in Table 1. Thermal properties of materials are from the values Clarke (2001) listed. The thermal mass of the internal wall and the first floor was taken account into the thermal capacitance of the zone. The infiltration rate is set at 0.75 air change per hour. The further source of ventilation was not considered due to high infiltration rate. As a simplification, no internal heat gains were added into the model.

Simulation conditions

The simulation was carried out during the winter from October to March for 6 months with 5 min simulation interval. The meteonorm weather data is used for this study. The location is London having the maximum temperature of 19 °C, the minimum temperature of -3 °C and the average temperature of 7 °C during the winter. There are two temperature settings. The one is constant room temperature setting at 21 °C. The other is night setback room temperature setting; 21 °C for 7:00 – 22:00, 17 °C for 22:00 – 7:00. This is one of common household scenarios from Marshall (2011).

The heat demand was 7.8 kW under the design ambient temperature of – 2 °C and the set room temperature of 21 °C. To evaluate the performance difference between 2DOF and the other conventional control strategies in night setback mode properly, the design capacity of radiator was set as 10 kW under the design surface temperature of 60 °C and the design air temperature of 20 °C for satisfying heat demand under the heating up phase.

Control strategies settings

2DOF was compared to the three other temperature control strategies. The details and their settings for simulations are as follows. 2DOF and FB have the same range of supply water temperature from 25 to 60 °C. Heating function stops while 2DOF and FB calculate water temperature of lower than 25 °C. CWT and HC have a system stop and start function as follows; the heating system turns off when the room temperature goes over the set temperature plus 1 °C and turns on when the room temperature goes under the set temperature minus 1 °C.

- CWT: Supply water temperature is constant at 55 °C when the heating system is on.
- HC: Supply water temperature settings are separately 55 °C at the low ambient temperature of -2 °C and 40 °C at the high ambient temperature of 15 °C when the heating system is on. The low ambient temperature is same as the design ambient temperature of London. The other temperatures are same as the medium setting De La Cruz (2015) described.
- FB: The parameters were determined based on the simulation results in night setback room temperature setting under the ambient temperature of 7 °C. The gain and the integral time are 2 °C/K and 3600 s for 0 % overshoot.

Table 2: RMSE and maximum absolute deviation under constant room temperature setting.

	CWT	HC	FB	2DOF
RMSE[°C]	0.59	0.51	0.20	0.20
Maximum absolute deviation [°C]	1.11	1.28	1.00	1.18

- 2DOF: The initial value of coefficient α is 1.3. The coefficient β is 25. The parameter N is 288 which is equivalent to 1 day divided by the simulation interval of 5 mins. The FB parameters are the gain of 2 °C/K and the integral time of 3600 s as the conventional FB parameters.

Simulation results

- Constant room temperature setting

To evaluate the operating performances under the constant room temperature setting, the following two indicators were used in this study: Root Mean Square Error (RMSE) and maximum absolute deviation from set room temperature. RMSE and the maximum absolute deviation of the control strategies are shown in Table 2. 2DOF and FB showed the best performance in the RMSE of 0.20 °C. On the other hand, FB showed the best performance in the maximum absolute deviation of 1.00 °C. The monthly maximum absolute deviation is shown in Figure 3. Figure 3 shows that 2DOF showed worse performance in the maximum absolute deviation than FB only in December. This phenomenon happened once due to a sharp ambient temperature increase of 7 °C for an hour. The direct response function to ambient temperature caused the maximum absolute deviation. Excluding this period, the maximum absolute deviation in December was 0.73 °C that was lower than the maximum absolute deviation during the winter of FB. Regarding the other two control strategies, CWT showed the similar performances in all the months and there were large performance differences with HC. The relationship between water and ambient temperature of 2DOF and HC were compared in Figure 4. HC seems to be higher than the heat load profile of the house under high ambient temperature. During the winter, the coefficient α of 2DOF changed from 1.3 to 2.4 and was 1.6 on average. This means that the water temperatures calculated from 2DOF's direct response function to ambient temperature were separately 62 °C at the low ambient temperature of -2 °C and 35 °C at the high ambient temperature of 15 °C on average.

Figure 5 shows room and water temperature trends of 2DOF and FB on the 10th January with the minimum ambient temperature during the winter. FB showed large room temperature up and down during the daytime

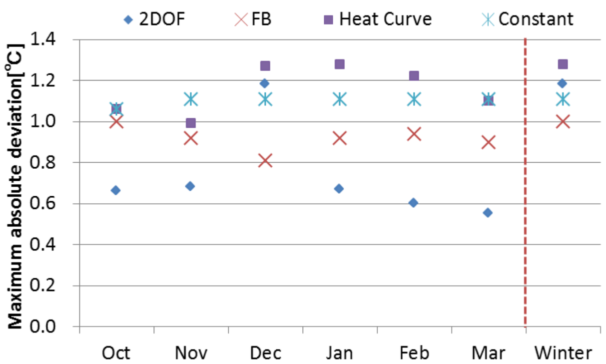

Figure 3: Monthly maximum absolute deviation under constant room temperature setting.

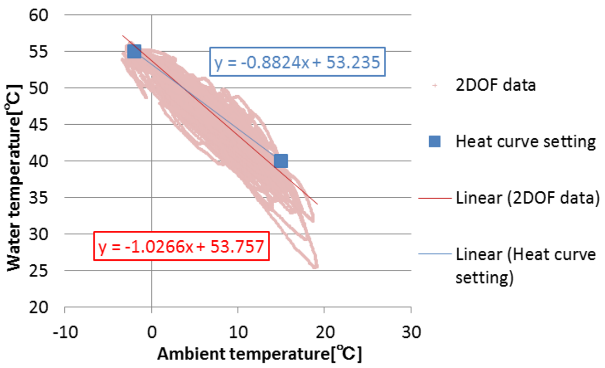

Figure 4: Comparison relationship between water and ambient temperature of 2DOF, and HC settings.

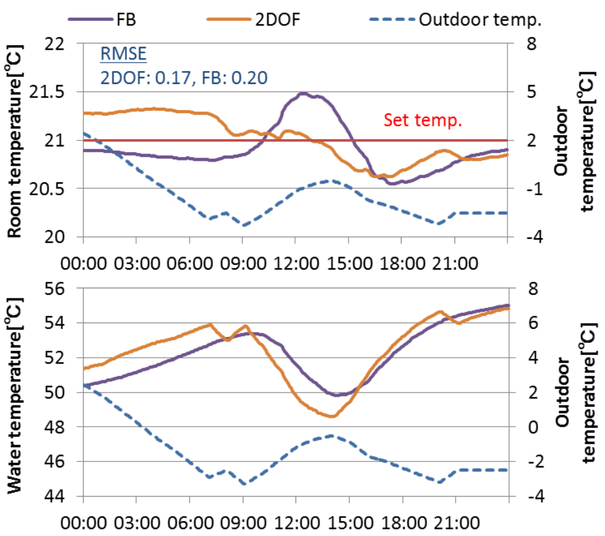

Figure 5: Room and water temperature trends under constant room temperature setting on the 10th January.

according to outdoor temperature changes. On the other hand, 2DOF decreased water temperature according to ambient temperature up and prevented the room temperature from increasing. The daily RMSE of 2DOF was smaller than FB. The direct response function to ambient temperature seems working well in this case.

In conclusion, 2DOF generally showed better performances than the other control strategies under the constant room temperature setting even though there was an exception.

- Night setback room temperature setting

For the operating performances evaluation under the night setback temperature setting, the following three indicators were used in this study; time to reach target room temperature, maximum absolute deviation and RMSE after reaching target room temperature. The time count starts when set temperature changes and ends when room temperature reaches 17.5 °C in step-down and 20.5 °C in step-up. The maximum absolute deviation and the RMSE are calculated since room temperature reaches 17.5 °C in step-down and 20.5 °C in step-up until next step-down or step-up.

Table 3: Performances under night setback room temperature setting.

	CWT	HC	FB	2DOF
Time to reach target temperature [min]	60	256	182	123
Maximum absolute deviation [°C]	1.08	1.08	0.91	1.19
RMSE after reaching target temperature [°C]	0.40	0.31	0.15	0.13

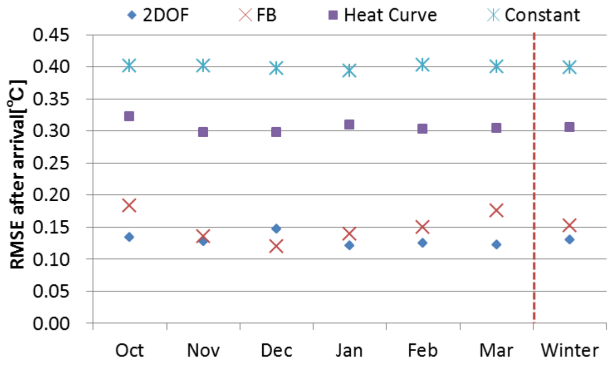

Figure 6: Monthly RMSE after reaching target room temperature under night setback room temperature setting.

The time, the maximum absolute deviation and the RMSE are shown in Table 3. 2DOF showed the best performance in the RMSE with 0.13 °C and the second best in the time with 123 min which is 30% faster than FB. FB showed the second best performance in the RMSE with 0.15 °C. CWT was the fastest to reach target temperature. Room temperature could not reach the target in step-up with HC on the many days. Ambient temperature during the daytime is generally higher than the night-time whereas heat demand is high in step-up compared to keeping room temperature. HC seems to need an adjustment scheme in step-up. On the other hand, HC was the fastest in step-down with 46 min. The second fastest in step-down was CWT with 50 min. During the winter, the coefficient α of 2DOF changed from 1.2 to 2.4 and was 1.5 on average.

The monthly maximum absolute deviation and RMSE are separately shown in Figure 6 and 7. Both of them tell that 2DOF showed the best performances except for December. The maximum absolute deviation of 1.19 °C happened during the same period and for the same reason as the constant room temperature setting. Excluding this period, the maximum absolute deviation in December and during the winter were separately 0.50 °C and 0.56 °C. The maximum absolute deviation of 0.56 °C was lower than FB.

Figure 8 shows room and water temperature trends of 2DOF and FB on the 10th January same as the constant temperature setting. 2DOF showed sharper increase of water temperature, quicker approach to the set room temperature and smaller overshoot than FB in step-up.

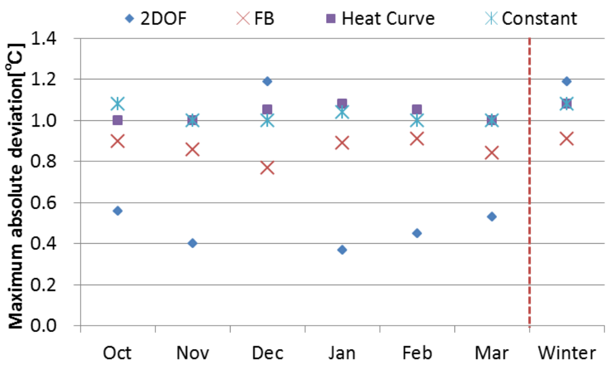

Figure 7: Monthly maximum absolute deviation after reaching target room temperature under night setback temperature setting.

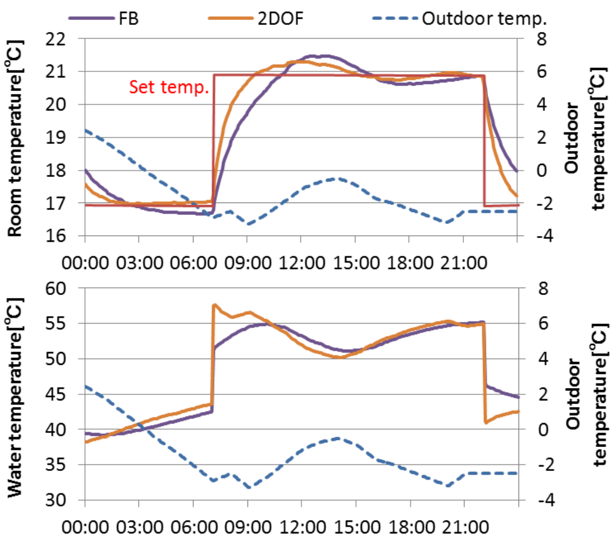

Figure 8: Room and water temperature trends under night setback room temperature setting on the 10th January.

The overshoot did not appear and the room temperature dropped quickly into the set temperature with 2DOF in step-down. The feed forward function of 2DOF seems improving followability to the change of a target value.

Based on the analysis, it was verified that 2DOF usually shows better performances than the other control strategies under the night setback room temperature setting.

Conclusion

This paper showed the operating performance of this 2DOF approach was evaluated by simulation compared to the three other conventional controls; CWT, HC and FB. The simulation was carried out during the winter for 6 months with weather data of London under the two temperature settings; constant room temperature setting and night setback room temperature setting. The simulation results revealed the following things;

1. Constant room temperature setting

- There was no significant difference between 2DOF and FB in terms of deviations from a set point.
- 2DOF showed better performance in reducing maximum absolute deviation with an exception of 1 day among 182 days.
- The direct response function to ambient temperature of 2DOF generally worked well whereas it did not work well when a very sharp ambient temperature change happened such as 7 °C for an hour.

2. Night setback room temperature setting

- 2DOF reduced deviations from and reached a set point 30% faster than FB.
- 2DOF showed better performance in reducing maximum absolute deviation after room temperature's reach to a set temperature with an exception of 1 day among 182 days.
- The feed forward function of 2DOF improved followability to the change of a target value.
- The direct response function to ambient temperature of 2DOF generally worked well whereas it did not work well when a very sharp ambient temperature change happened same as under constant room temperature setting..

As a conclusion, the simulation results verified the improvement potential of room temperature control by 2DOF. On the other hand, it was found that a measure is required for further improvement in the direct response function to ambient temperature of 2DOF to tackle with sharp weather changes. In future work, internal heat gains will be taken into the model and more comprehensive system dynamics analysis will be carried out with an enumerated set of assumptions such as a variety of room temperature settings.

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