A study of static and dynamic feed-forward in temperature control of buildings

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ABSTRACT
In most temperature control systems, the control strategy is based on feedback of the output signal (measured value). In this paper, however, control strategies with both feedback and feed-forward are investigated and discussed. In particular, we discuss feed-forward from internal disturbances, such as lighting and electrical machines. We also compare and discuss the differences between static feed-forward, dynamic feed-forward and no feed-forward at all.

It is shown that a control strategy based on both feedback and feed-forward often reduces the energy consumption as well as improves the control performance (smaller temperature variations) compared with a control strategy without feed-forward. Furthermore, it is shown that dynamic feed-forward in general gives better performance than static feed-forward and that static feed-forward gives better performance than no feed-forward at all. It is also shown how the performance of different control strategies depends on the frequencies of the disturbances.

INDEX TERMS
HVAC control systems; Feedback; Energy savings; Static feed-forward; dynamic feed-forward

INTRODUCTION
The temperature control of most buildings is based on feedback control, which means that the value of the control signal is based on measurements of the controlled output (indoor temperature). However, in a system with both feedback and feed-forward, the controller also uses signals from measurable disturbances to control the indoor temperature more effectively. Figure 1(a) shows a system with only feedback whereas Figure 1(b) shows a system with both feedback and feed-forward. In this paper, it will be studied how control strategies without feed-forward, with dynamic feed-forward and with static feed-forward affect the energy use and the temperature variations for a building. The feedback control system in Figure 1(a) has a number of well-known advantages, which explains the extensive use of feedback systems in industrial applications today. Two important advantages using feedback control are that these systems normally give better attenuation of low-frequency process disturbances and better robustness (less sensitivity to parameter changes) when compared to systems without feedback. However, it is also a well-known fact that the damping of process disturbances can often be further improved when using feedback control in combination with feed-forward control from measurable disturbances (Underwood, 1999).

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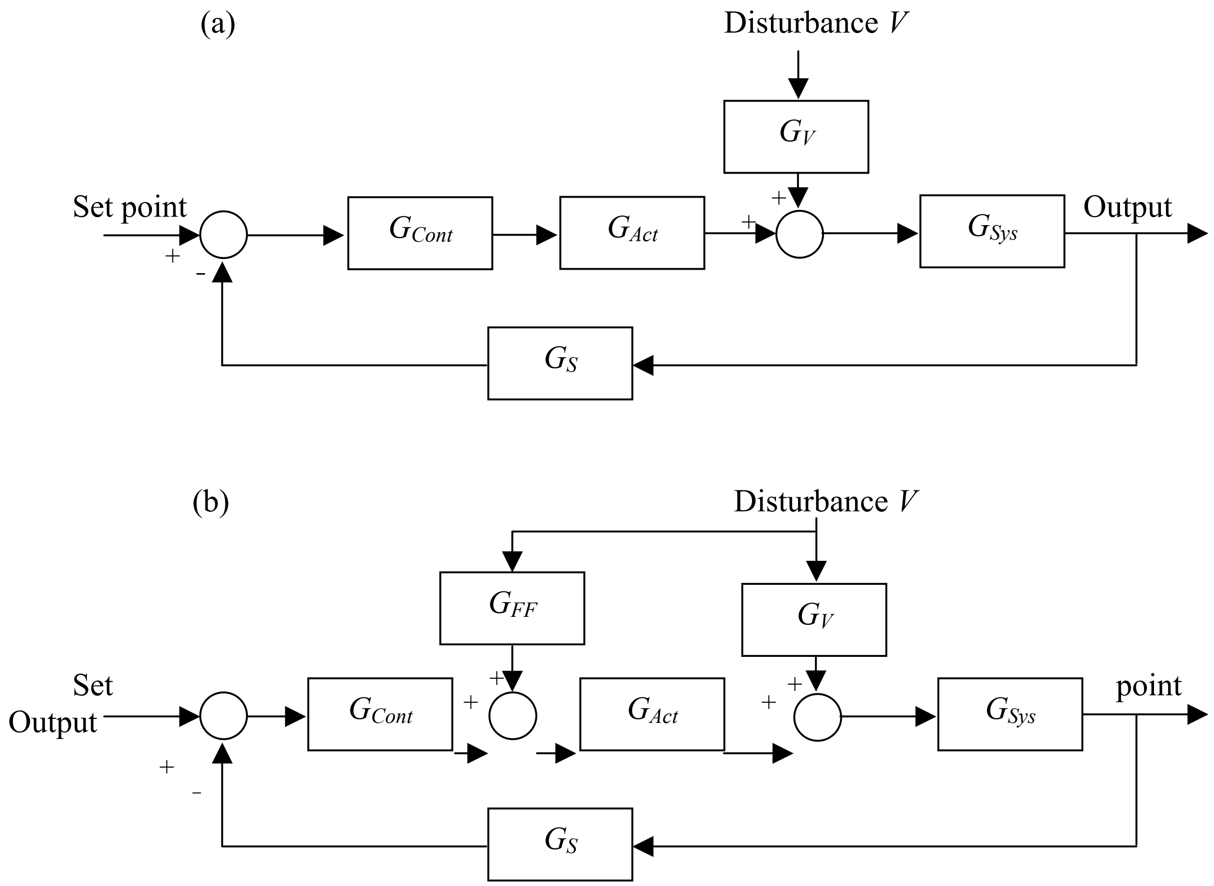

Figure 1 (a) General feedback control system. (b) Control system with feed-forward— G_{Cont}, G_{Act}, G_V, G_{Sys}, G_{S} and G_{FF} are the transfer functions for controller, actuator, disturbance, building, sensor and feed forward compensator, respectively.

A feed-forward controller uses information from measurable disturbances to improve the control performance. In order to eliminate the disturbance V, the following relationship must be fulfilled:

$$V \cdot G_{\text{FF}} \cdot G_{\text{Act}} = -V \cdot G_V$$

It means that the dynamic feed-forward transfer function G_{FF} must be:

$$G_{\text{FF}} = \frac{-G_V}{G_{\text{Act}}}$$

Theoretically, it is possible to eliminate the disturbance completely using dynamic feed-forward, provided the transfer function G_{FF}, calculated by the above equation, is stable and possible to realize. In practice, however, the disturbances will often not be perfectly eliminated, partly because of the fact that the transfer functions G_V and G_{Act} may not be exact and partly because there are other *non-measurable* disturbances that affect the process. Another problem is that the controller transfer function G_{FF} is sometimes difficult to implement. In order to avoid the latter problem and reduce the complexity of the feed-forward link, static feed-forward may be used. The static feed-forward transfer function will be a constant as:

$$G_{\mathrm{FF}} = \frac{-G_V(0)}{G_{\mathrm{Act}}(0)}$$

The purpose of this paper is to investigate and highlight the advantages of using feed-forward compared to a traditional feedback control system and in particular to compare dynamic feed-forward, static feed-forward and traditional feedback (no feed-forward at all) systems.

METHODS

Modelling

In order to compare different strategies for temperature control, we have studied a small room of 11 m^2. The mathematical model of the room was obtained by a combination of theoretical modelling and experimental identification (Soleimani-Mohseni, 2002). Through theoretical modelling a third order state-space model was first obtained. In this model, the indoor radiator power P (W) and the outdoor temperature T_{U} (°C) are the input signals, and three different temperatures (one inside the building and two in the walls of the building) are the state variables. The indoor temperature T (°C) is the output signal. The constants of the state-space model have then been adjusted using step-response identification and measurements in steady state. The transfer function model of the building is given below. The step-response of the model together with one experimentally obtained step-response is shown in Figure 2. The height of the input step was $P = 2000$ W at time $t = 0$.

$$G_{\mathrm{Sys}} = \frac{T}{P} = \frac{1 \cdot 10^{-6} s^2 + 1.314 \times 10^{-9} s + 2.66 \times 10^{-13}}{s^3 + 0.00163 s^2 + 5.272 \times 10^{-7} s + 3.538 \times 10^{-11}}$$

$$G_V \times G_{\mathrm{Sys}} = \frac{T}{T_{\mathrm{U}}} = \frac{1.415 \times 10^{-7} s + 3.538 \times 10^{-11}}{s^3 + 0.00163 s^2 + 5.272 \times 10^{-7} s + 3.538 \times 10^{-11}}$$

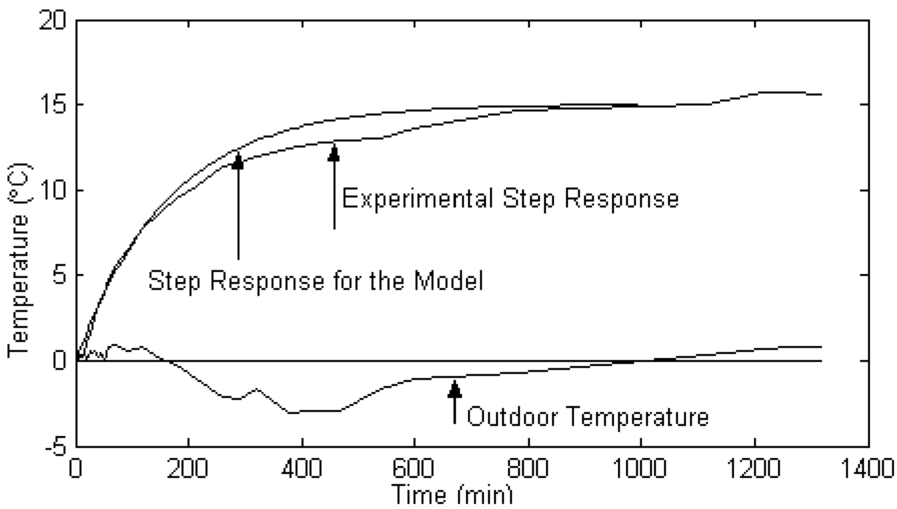

Figure 2 Experimental step-response for the building as well as the step-response for the model and the outdoor temperature during the step response experiment

Simulation and Simulation Conditions
For simulation purposes, the building and the temperature control system has been modelled in a Matlab-Simulink model environment (Thomas and Soleimani-Mohseni, 2001). The performances of different control systems in the experimental building have been simulated under the following conditions and assumptions:

- It is assumed that the building is heated by a heating source (for example, an electrical radiator). It is also assumed that the dynamics of the heating source can be described by a first-order transfer function with a time constant of 25 min.
- There is a constant heating effect of 100 W in the building, which represents one person working or living in the building.
- The maximum heating power of the heating source is 3000 W.
- The set point for the temperature control system is 21°C. (all simulations have been started from a steady state with 21°C inside the building).

Further, it is assumed that there is some electrical machine inside the building, which acts as a disturbance. In the simulations, the electrical machine has been switched on and off at regular intervals with a duty cycle of 50%. The period has varied between 1 and 8 h. When the electrical machine is turned on, it gives a heating power of 1500 W. This heating power gives rise to fluctuations in the indoor air-temperature. The electrical machine may, for example, represent an oven, a drilling machine, a photocopier or any other heat-producing machine. In the simulations presented here, no other disturbances have been assumed. In this paper, we do not discuss whether the building is water-heated, electrically heated or air-heated. The real dynamics of the heating source may, of course, be more complex than the models used here. In practice, many systems are both non-linear and time-variable. However, even if the models of the actuators and heating systems are simplified, it is believed that the main results hold true even for practical systems, since the dynamics of the heating devices have short time constants compared with the time constants of the building.

Controller Strategies and Measures of Performance
The following controller strategies will be compared to each other:

- *P-control (P)*. A proportional controller with a maximum heating power of 3 kW and a proportional constant of 1600 W/°C. This type of controller strategy is common in many temperature control systems of today (Trüschel, 1999).
- *P-control with dynamic feed-forward (PFF)*. The same P-controller as above, but combined with a dynamic feed-forward compensator from the electrical machine.
- *P-control with static feed-forward (PFFs)*. The same P-controller as above, but combined with a static feed-forward compensator from the electrical machine.

In this paper, the following two measures have been used to compare the performance of the different controllers:

- The *total effective energy consumption* Q (kW h) during 24 h at stationary conditions.
- The *maximum temperature difference* ΔT_r (°C), i.e. the difference between the maximum temperature and the minimum temperature during 24 h.

The total effective energy consumption during 24 h is calculated as the time integral of the thermal power $P(t)$ from the heating source (radiator or convector):

$$Q = \int_{t=0}^{24\cdot 3600} P(t)\mathrm{d}t$$

Of course, it is desirable that the total energy consumption Q is as low as possible and that the maximum temperature difference ΔT_r is small. Both these measures are important when comparing the performance of different controllers. Some other measures that may also be important to study are the maximum temperature deviation from the set point, the average indoor temperature, the standard deviations for the temperature and the total energy cost. However, in this paper, we have concentrated on the first two measures (Q and ΔT_r).

RESULTS

A comparison of the three control strategies above, for outdoor temperatures 7 and 0°C have been done. In Figures 3 and 4, the energy consumption Q (kW h) and the maximum temperature difference ΔT_r (°C) are shown for the three controllers for 7 and 0°C, respectively. The total simulation time is 24 h and the simulated outdoor temperatures are constant at 7C and 0°C in this simulation. Other outdoor temperatures and other controllers than those mentioned above, such as P-controllers with or without dead band, with or without cooling and with or without feed-forward have also been investigated. The results from these investigations show that a more extensive use of feed-forward from internal disturbances might be very advantageous in many temperature control applications. It gives better controller performance, and, at the same time, it will reduce the energy use. In certain situations, HVAC-control systems with both heating and cooling may be replaced by systems without cooling when using feed-forward. However, the potential for improvements depends on factors such as the type of building, the type and the frequencies of disturbances, the outdoor temperature and so on (Soleimani-Mohseni, 2002).

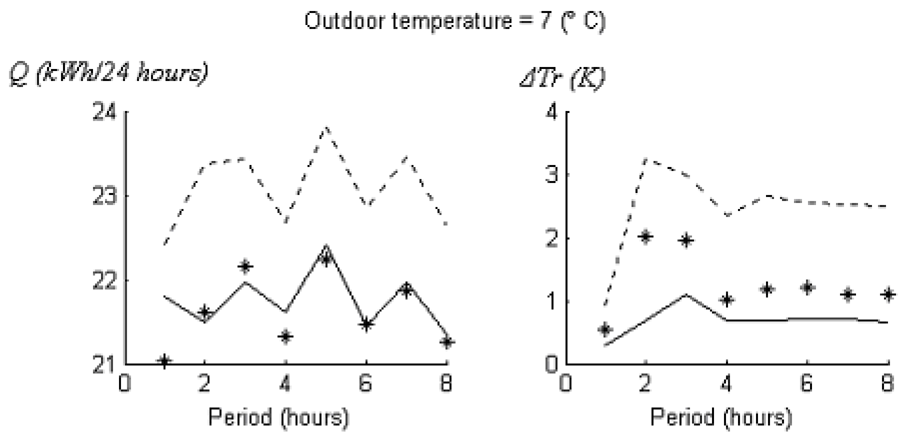

Figure 3 Energy use Q (kW h/24 h), the maximum temperature difference ΔT_r (°C) versus period (h) for outdoor temperature 7°C. P, dotted line; PFF, solid line; PFFs, asterisks.

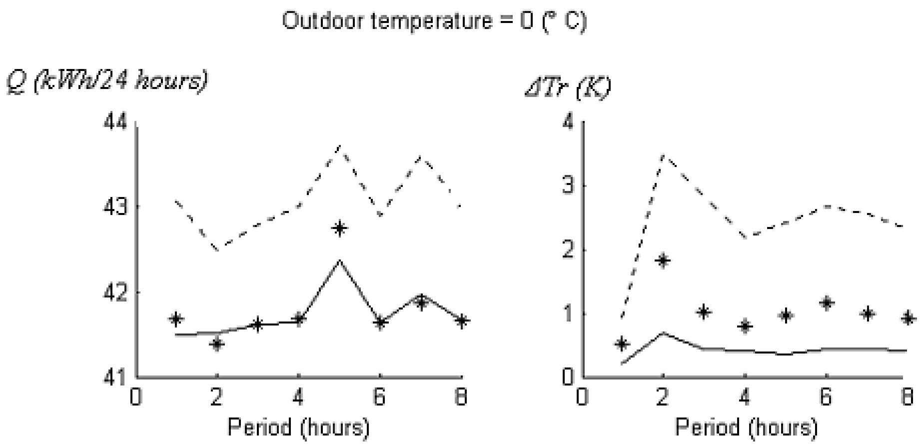

Figure 4 Energy use Q (kW h/24 h), the maximum temperature difference ΔT_r (°C) versus period (h) for outdoor temperature 0°C. P, dotted line; PFF, solid line; PFFs, asterisks.

CONCLUSIONS

The comparisons show that dynamic feed-forward is clearly better than static feed-forward, when looking at the temperature variations. At the same time, static feed-forward is clearly better than no feed-forward at all. The result shows that dynamic feed-forward should be used if possible. Annual energy use and mean temperature range (°C) for the whole year have also been investigated (but not shown here, see Soleimani-Mohseni, 2002) and the results from these investigations show that PFF controller gives a much smaller mean temperature range than P-controller. Sometimes it may be possible to replace a P-controller with both cooling and heating by a PFF controller (without cooling) and thus save the cost for AC-installation since there is no more need for cooling. For other buildings or rooms, the need for cooling may be restricted to a shorter time of the year than before, when feed-forward controllers are used more extensively. In short, the advantage of feed-forward controllers depends on their ability to compensate for disturbances more quickly than ordinary feedback controllers. For example, when the PFF controller gets the information that the extra heating source (i.e. some machine) has been switched on, it *immediately* decreases the power of the heater. A conventional controller will not respond that quickly, since the extra heating source will not immediately give rise to an increased temperature at the measurement transmitter. There is often a time constant of 15–45 min in commonly used measurement transmitters for indoor temperature. As a result, when using a PFF controller, there will be a better reduction of large over-temperatures, and the need for cooling will decrease.

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