CLASSIC AND ADVANCED MODELS FOR CONTROLLING HVAC SYSTEMS IN A UNIVERSITY BUILDING

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ABSTRACT

In this work a systematic procedure for the modelling and simulation of an HVAC (Heat Ventilating and Air Conditioning) thermal system is reported. The dynamic behaviour of each element, not only on its own but also as part of the whole process, is analysed and tested. The basic principles of energy conservation and heat transmission are applied to model the various processes that usually occur in thermal installations. An experimental building was used to evaluate the proposed energy control; it was also used to identify methods for modelling both particular elements and the whole system. Following validation of the model, new control strategies for the process, with classic and advanced algorithms and procedures, are proposed with a view to achieving both comfort and important energy savings.

Keywords: Simulation, HVAC System (Heat Ventilating and Air Conditioning), MPC (Model Predictive Control).

1. INTRODUCTION

Energy consumption in domestic and public buildings accounts for almost 30% of the total energy consumption of the European Union. CO_2 pollution due to maintaining comfortable temperatures inside buildings represents a similar percentage. Considerable efforts are now under way to reduce energy waste in thermal installations; such efforts involve several aspects, such as creating new elements and materials and research into new control and management systems. The two main goals underlying these endeavours are comfort and energy savings. Naturally, even small energy savings in an individual module will afford appreciable benefits when the strategies proposed here are applied in larger scale.

The relationship between a building's architecture and its thermal engineering can be found in (Kuehn et al. 1998). In (García-Sanz 1997) the author reports an analogy between electrical circuits and thermal systems and uses it to model room temperatures. In previous works (Mathews et al. 1999; Riederer 2002; Stec et al. 2005) the authors applied different methods to analyse and study the problem in specific systems. In this sense, a systematic study, both theoretical and experimental, can be found in (Liao et al. 2005). Important contributions in this field include a modular thermal model with heat transfer between zones, affording a system of stochastic differential equations with statistical estimation of their parameters (Andersen et al. 2000), and a recent work with a model predictive control strategy (Shui et al. 2006).

In the present work a systematic procedure for the modelling and simulation of a real HVAC thermal system is reported. Based on real data from an experimental building, identification procedures are generated in order to calculate and estimate the unknown parameters of the process. The model is then validated, taking into account the same experimental data collected along the general system function. New control strategies for the process are proposed, using classic and advanced algorithms and the procedures are tested in order to achieve both comfort and important energy savings.

2. PROCESS DESCRIPTION

The three main elements of the HVAC system (Fig. 1) modelled here can be classified thus:

- Energy-producing units (Boiler and Cooler)
- Energy-exchange units (Air Handling Unit and radiators)
- Zones/Rooms

In these types of system, it is common that there will be coupled signals and fluid flow feedbacks (of air and water) that make analysis of the dynamics of the system both tedious and complex. This situation produces non-linear equations, time delays, and non-homogenous characteristic dynamics. Additionally, there are further elements and signals which must be taken in to account:

- Fluid transmission elements (pipelines, ducts)

- Flow control elements (thermostats, three-way-valve electronic regulators, variable air volumes)
- Classic and advanced controllers (PID, Model Predictive Control)
- Internal and external disturbances (external temperature, solar radiation, occupancy and lighting).

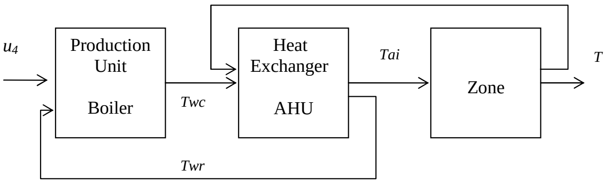

Figure 1: General scheme of an HVAC system

Many of these elements have been modelled in different ways; some of the models are fairly simple and others are somewhat more convoluted and complex. Choice of the most appropriate model depends on its intended application (design, control, or education). For instance, models for the indoor zones of buildings may be described by means of first-order linear equations, although it is also possible to use non-linear models with high-order dynamics. Under general assumptions the governing equations of the main elements are:

<u>Zone model</u>

$$\begin{aligned} C_R \frac{dT}{dt} &= -\rho_a c_a (T - T_{ai}) u_1 q_R - (UA)_v (T - T_{ex}) - \\ &- (UA)_{pi} (T - T_p) + Q_p \\ C_p \frac{dT_p}{dt} &= -(UA)_{pe} (T_p - T_{ex}) + (UA)_{pi} (T - T_p) \end{aligned} \tag{1}$$

<u>Heat Exchanger (Air Handling Unit - AHU)</u>

$$\begin{aligned} C_a \frac{dT_{ai}}{dt} &= -\rho_a c_a q_a T_{ai} + \\ &+ \rho_a c_a (u_3 q_a T_{ex} + (1 - u_3) q_a T) + (UA)_{AHU} (T_{wr} - T_{ai}) \\ C_w \frac{dT_{wr}}{dt} &= -\rho_w c_w q_w T_{wr} + \rho_w c_w (u_2 q_w T_{wc} + \\ &+ (1 - u_2) q_w T_{wr}) - (UA)_{AHU} (T_{wr} - T_{ai}) \end{aligned} \tag{2}$$

<u>Production Unit (Boiler)</u>

$$\begin{aligned} C_c \frac{dT_{wc}}{dt} &= \rho_w c_w u_2 q_w T_{wr} - \rho_w c_w u_2 q_w T_{wc} - \\ &- (UA)_c (T_{wc} - T) + \eta P_N u_4 \end{aligned} \tag{3}$$

<u>Nomenclature</u>

C	*overall thermal capacitances: zone (C_R), walls (C_p), air in the AHU (C_a), water in the AHU (C_w) and boiler (C_c)*
c	*specific heat of air (c_a) or water (c_w)*
ρ	*air density (ρ_a) or water density (ρ_w)*
q	*volume flow rates: supply air in the zone (q_R) or in the AHU (q_a) and water in the AHU (q_w)*
Q_p	*heat gains from occupants and lighting*
(UA)	*overall heat transfers: windows $(UA)_v$, external walls $(UA)_{pe}$, internal walls $(UA)_{pi}$ and boiler $(UA)_c$*
$(UA)_{AHU}$	*overall transmittance area factor of the AHU*
T	*zone measured temperature*
T_{ai}	*supply air temperature*
T_{ex}	*outside temperature*
T_p	*inner wall temperature*
T_{wc}	*water supply temperature in 3- way valve*
T_{wr}	*water return temperature in 3- way valve*
u_1	*damper zone control*
u_2	*three way valve position*
u_3	*outside air damper position*
u_4	*gas/fuel flow rate*
η	*boiler efficiency*
P_N	*nominal power*

The models obtained here follow a block-oriented approach; *Matlab/Simulink* was selected as the simulation toolbox used to study, analyse, and design partial and general simulation scenarios. A new library, known as HVAC, was built in order to simplify model generation, and also for use as a tool to interpret the simulation results.

The availability of real data, coming from a university building where an HVAC system is installed, enabled us to carry out tests to validate the partial and global models created; procedures for the identification of processes were also generated with these data. Once the HVAC model results have been confirmed by experimental data, new and improved control strategies could be designed.

3. REAL PROCESS AND MODELLING

As a demonstration of both the simulated process and the real one, figure 2 shows the block diagram, built n *MATLAB/Simulink* modules of a large space, the reading room of a University building which has been selected in this experiment. Input/output data collected from the real system that can be shown are: input heat flow rate, supply input air temperature, internal and external temperature and periodical starting/shutdown signals.

A functional block representing the zone model is included in the same file. In order to compare correctly the results of both systems, the real process and its model, the same external real signals (control and disturbances) act over the model.

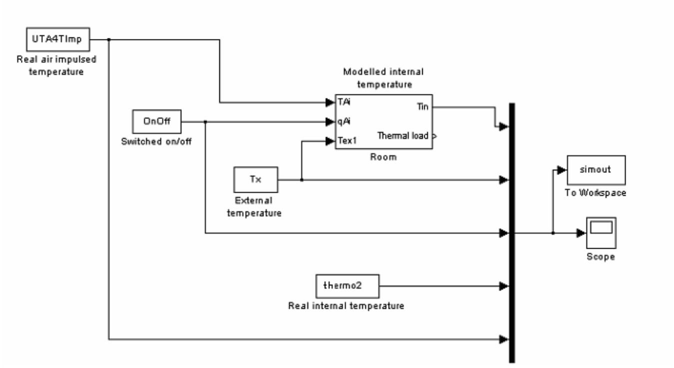

Figure 2: Real and modelled zone thermal system

The graphic results for room temperature during a given period of time are shown in figure 3. It is easy to observe a good fit between the simulated and experimental results. In this case, it was possible to achieve identification with a second-order system for indoor temperature, and a first-order model for air flow. Supply air temperature was used as the control variable, and outside temperature was taken as a disturbance input.

As shown in figure 3, it was not possible to achieve either the comfort or the energy expenditure goals during the period of time under consideration in the real system; again, a strong overheating and a rather poor energy performance can be observed from start to end. Basically, the reason was a fault in design, together with poor control strategy.

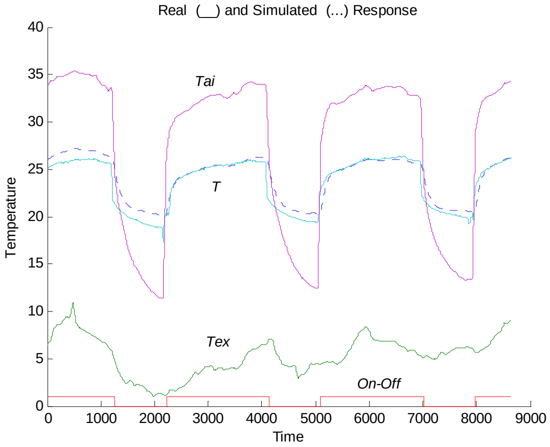

Figure 3: Real and modelled zone thermal results

However, by recording all the available signals during this period of time, allows identify the process, not only for the studied zone but also for the other dynamic elements in the system. This systematic method furnished partial or global models that were useful for testing and simulating future control strategies.

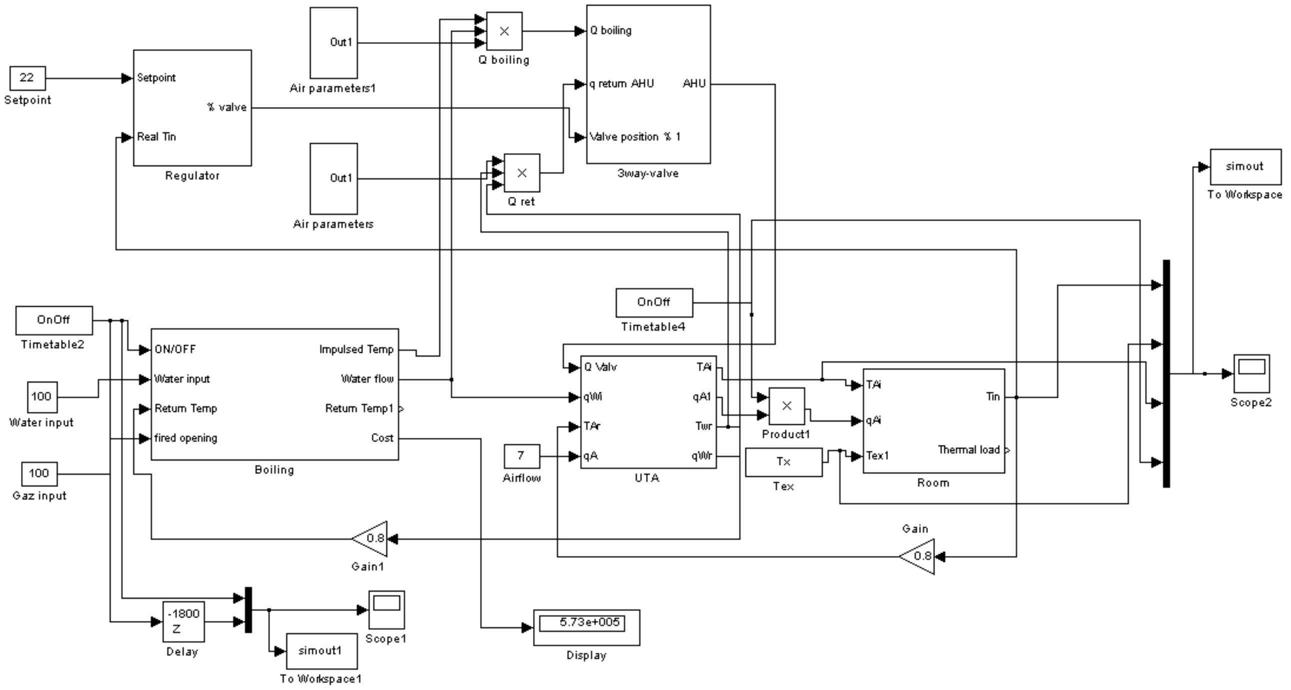

Figure 4: HVAC model system with 3-way valve regulator

4. CONTROL STRATEGIES

Once the model has been validated, alternative control strategies have been designed in order to improve performance having as objectives comfort and energy savings. Different subsystems representing the functional performance of physical elements have been taken into account. The unit production, the AHU, and the zone models are presented as complex blocks in *Simulink*. Signals, external data and input/output ports allow the interconnection of the main elements.

Special attention has been paid to the design of control units. In order to approximate this model to the practical situation in a building a three way valve has been modelled as the only actuator in the process.

Usually, the process control is carried out either using an ON/OFF controller or a conventional PID. Furthermore, most building installations use just a P controller due to the fact that a PI controller could seriously damage the valve and otherwise and small stationary errors in internal temperature are allowable in such large zones with great occupation rates.

Such a simple control which acts over the three way valve, in the sense of correctly mixing heat water flows from boiler and return ducts, is the base for interchanging energy with the air in the AHU which is the nucleus of HVAC system. The whole system *Simulink* model is presented in Fig. 4.

Figure 5 shows the results when a P controller (with a setpoint of 22ºC and a gain of 50) and a start/shutdown system were implemented. Small errors can be observed in the temperature variable due to the lack of integral action. Moreover the evolution of the supply air temperature is presented. There can be seen a small gap between both temperatures, which is enough to achieve the zone comfort, that is usually considered an interval from 20º to 22º in winter season.

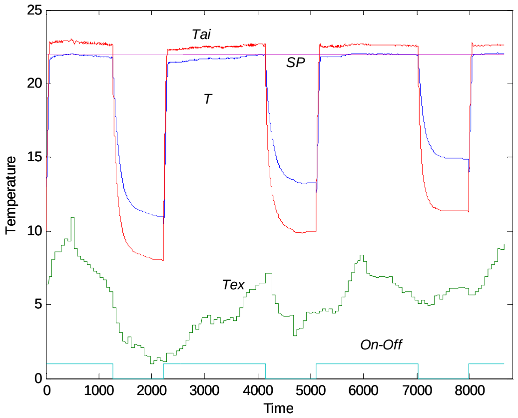

Figure 5: Simulation results with a 3-way-valve regulator

A model-based predictive control was also built. The aim of the zone model was to establish a strategy that would simultaneously reduce deviations from reference signals related to occupancy levels for different periods and the control effort needed to achieve this. This translates into the minimisation of a quadratic cost, taken as a reference index in which the weights, the prediction, and control horizons and restrictions can produce an enormous variety of strategies. It is then possible that these parameters could be subjected to multiple-criteria optimization, depending on the specific goals to be achieved by the thermal system. More precisely, it would be possible to consider an advanced control scheme; a Constrained Model Predictive Control based on the model already identified. This would suggest the optimization of a performance index based on minimization of the following function:

$$V(k) = \sum_{i=H_w}^{H_p} \left\| T(k+i:k) - r(k+i:k) \right\|^2_{Q(i)} + \\ + \sum_{i=0}^{H_u-1} \left\| \Delta u(k+i:k) \right\|^2_{R(i)} \tag{4}$$

In order to achieve a good tracking of the zone temperature T with respect to the various desired temperature set points r, the prediction horizon and the prediction control horizon, H_p and H_u, must be estimated. In order to obtain energy savings, this must occur during the operation time and must apply limits to the control signals.

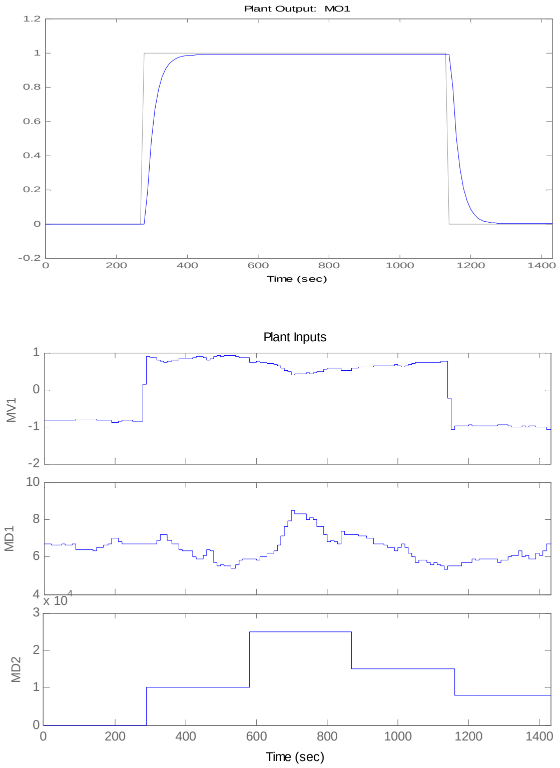

Figure 6: Restricted linear MPC room temperature

Two results are presented in this modern control design structure. The reference temperature profile is considered as step changes from a stationary state. The first is a restricted linear MPC with a linear zone model, where the control signal, manipulated variable, (*MV*) is the temperature of the air flow and the measured disturbances (*MD1* and *MD2*) are the external temperature and the zone occupancy (see Fig. 6).

The second is a restricted non-linear MIMO system: an MPC where the heat flow in the zone is not linear and where the control signals are the air-flow rate and the air-flow temperature (see Fig. 7). Simple interpretation of the results shown allows the thermal engineering to activate new control strategies with the perspective of comfort and energy saving.

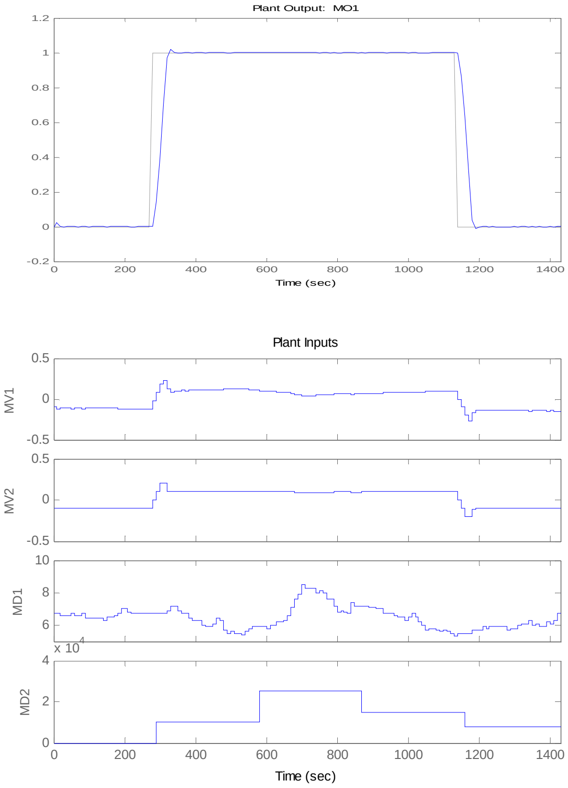

Figure 7: Restricted non-linear MPC room temperature

In order to achieve the best solutions, the parameters of the controller, such as the prediction horizon, the control prediction horizon and the weights in both the output error and in the control signals, *Q(i)* and *R(i)*, in the performance index must be selected in a multiobjetive index. Selecting the best control design parameters based on a new performance index, such as the L-infinite norm or ISE, has been done previously in activated sludge processes by some of the authors of this work (Francisco et al. 2005).

5. CONCLUSIONS

Here we have investigated a general procedure for deriving a dynamic model to control an HVAC system. The model consists of a zone, an air-handling unit, a production unit, and control elements. The mathematical models for the components are derived based on physical properties and element characteristics. Simulation of the complete HVAC system was analyzed both in real and modelled situations, with the observation of excellent coincidences. The good result obtained in this agreement is a hint as to how the operation of a HVAC system might be improved, even though some algorithms cannot be introduced into real control devices. Classic PID controllers and Model Predictive Controllers based on models were then analysed, which revealed an improvement in the transient behaviour and rejected the disturbances and hence contributed to comfort and energy saving.

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