2013 European Control Conference (ECC)
July 17-19, 2013, Zürich, Switzerland.

REPETITIVE CONTROL TO COUNTERACT THE EFFECT OF PEOPLE ON THERMAL COMFORT CONTROL

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***Abstract*— People usually spend most of the time inside buildings. Therefore, it is necessary to reach an optimal thermal comfort situation since thermal comfort has a direct effect on people's productivity. The use of appropriate control strategies can highly contribute to this purpose. Usually the own people's influence is not taken into account at the time to maintain an optimal thermal comfort. People enter and leave the building following certain pattern which is repeated from one day to another. This paper presents a Repetitive Control (RC) approach which can counteract this periodic behaviour. This controller anticipates the effects produced by the entries and outputs of the people. Moreover, this controller is complemented by a feedback controller in order to cancel the non periodic disturbances.**

Simulation results obtained from the application of this control strategy to a characteristic room of a building are included and commented.

I. INTRODUCTION

People usually develop their daily activities inside buildings. Users' welfare must not be put at risk [1] since their productivity is directly related with their thermal comfort. In order to achieve an optimal thermal comfort situation, different approaches can be considered, such as the construction of bioclimatic buildings, which incorporate passive strategies and make use of renewable energies. However, in some cases, and mainly due to the typical climate of the location, this approach by itself may be insufficient [2]. In these cases, it is necessary to use appropriate control strategies on Heating, Ventilation and Air Conditioning (HVAC) systems, with the main objective of providing comfortable environments [1], [3], [4], [5], [6].

An important factor, which has to be considered, is that there exist a strong influence of people on thermal comfort inside a certain environment, since by means of their daily activities inside buildings they add heat to the environment, which derives in an increment of the indoor air temperature inside it. Thus, it is advisable to take into account this effect in order to develop an appropriate control system. In some places, as offices or laboratories, where the entries and outputs of people follows a periodic pattern it is possible to anticipate to the changes in the indoor air temperature.

Therefore, in this work, a Repetitive Controller (RC) to counteract the effect of people on thermal comfort is proposed. The RC controller allows to cancel these periodic disturbances. Repetitive Control [7], [8] is a well established, Internal Model Principle [9] based technique which allows tracking/rejecting periodic signals of known frequency. The key idea is that the performance of a system that executes the same task multiple times can be improved by learning from previous executions (iterations); this is the essence of RC.

Moreover, the RC strategy has been applied in simulation with a non linear model of a room. This model has been validated with real data from a real bioclimatic building, the CDdI-CIESOL-ARFRISOL building, although the results obtained with this control strategy can be easily extrapolated to any room of a building with a suitable network sensors and a periodic pattern for the people's entries and outputs. The RC controller is compared with a typical feedback controller in order to show its improvements at time to cancel the disturbances produced by people when optimal thermal comfort is pursued.

The paper is organized as follows: Section 2 includes an overview of the thermal comfort concept and a brief description of its estimation procedure through the Predicted Mean Vote (PMV) index. Section 3, is devoted to the model of the room used for simulation. The proposed control strategy is explained in Section 4. In Section 5 the obtained results are widely analyzed. Finally, in Section 6, the main conclusions are summarized.

II. THERMAL COMFORT

Most part of international standards, such as *ISO 7730* [10] and *ASHRAE 55* [11] define thermal comfort just as: *"That condition of mind which expresses satisfaction with the thermal environment"* [12]. However, by means of this definition it can be inferred that comfort is a cognitive process which depends of different kinds of processes, such as, physical, physiological or even psychological aspects [13]. Furthermore, thermal comfort sensation depends on several circumstances, such as the air temperature, the season of the year, the place where the human is, how much time he is in,

*The authors are very grateful to Andalusia Regional Government (Consejería de Economía, Innovación y Ciencia), Spain, for financing this work through the Programme "Formación de personal docente e investigador predoctoral en las Universidades Andaluzas, en áreas de conocimiento deficitarias por necesidades docentes (FPDU 2009)". This is a programme co-financed by the European Union through the European Regional Development Fund (ERDF). José Domingo Álvarez is a fellow of the Spanish 'Juan de la Cierva' contract program. This work has been partially funded by the following projects: DPI2010-21589-C05-04, DPI2010-15110, DPI2008-05818 (financed by the Spanish Ministry of Science and Innovation and EU-ERDF funds); PHB2009-0008 (financed by the Spanish Ministry of Education; CNPq-BRASIL; CAPES-DGU 220/2010).

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etc. However, different studies performed in this area have demonstrated that the air temperature that people choose for thermal comfort under similar conditions of physical activity, clothing, air velocity and relative humidity is very similar even though climates, living conditions and cultures differ around the world [13].

There exist many indexes in the bibliography to estimate thermal comfort conditions inside a certain environment [14]. However, the most extended index is the PMV (*Predicted Mean Vote*), which is able to predict the average response about thermal sensation of a large group of people exposed to certain thermal conditions for a long time [15]. The value of this index is a seven-point thermal sensation scale: 0 neutral, ±1 slightly warm/cool, ±2 warm/cool, ±3 hot/cold. In addition, PMV index formulation is based on the energy balance of the human body, considering this as a whole entity. Therefore, PMV index can be estimated as follows:

$$PMV = [0.303 \exp(-0.036M) + 0.028]L \qquad (1)$$

where M stands for human activity (metabolic rate) in $[\mathrm{W/m^2}]$ and L is the thermal load in the human body $[\mathrm{W/m^2}]$ defined as the difference between the internal heat production and the heat lost which happens when the person is in a thermal situation. More information about the procedure to estimate this index can be found in [14]. L can be estimated as:

$$\begin{aligned} L &= (M-Q) - 0.0014M(34 - T_{air}) \qquad (2)\\ &- 3.0510^{-3}[5733 - 6.99(M-Q) - p_a]\\ &- 0.42(M - Q - 58.15)\\ &- 1.7210^{-5}M(5867 - p_a)\\ &- 39.610^{-9} f_{cl}[(T_{cl}+273)^4 - (T_{mr}+273)^4]\\ &- f_{cl}h_c(T_{cl} - T_{air}) \end{aligned}$$

where Q stands for the external work $[\mathrm{W/m^2}]$, that is, the work performed by muscles during a certain task, p_a is the partial water vapor pressure in the air in [Pa]. As p_a can not be directly measured it is estimated from the relative humidity, H_r, noting that H_r is defined as the relation between partial water vapor pressure in the air, p_a, and saturated water vapor pressure at given temperature (which is tabulated). T_{air} stands for the air temperature in [K], T_{mr} is the mean radiant temperature in [K], h_c is the convective heat transfer coefficient $[\mathrm{W/(m^2K)}]$, f_{cl} is the clothing area factor [-] and T_{cl} is the clothing surface temperature in [K].

To guarantee thermal comfort conditions in a certain environment, international standards recommend to maintain PMV index value at 0 with a tolerance of ±0.5 [5].

III. ROOM MODEL BASED ON FIRST PRINCIPLES

As it has been previously introduced, the proposed control strategy has been simulated using the model and parameters of a room placed at the CDdI-CIESOL-ARFRISOL[1]. More specifically, the selected room is an office placed in the upper floor of the building and with a total volume of $4.96 \times 5.53 \times 2.8\ m^3$. It faces to North and is delimited by two rooms with similar characteristics. In addition, it has a window with a total surface of $2.15 \times 2.09\ m^2$ situated in the North wall, and it is equipped with a fancoil unit, that allows to regulate impulse air temperature controlling the fancoil velocity.

Therefore, it has been necessary to develop a model capable to represent its behaviour properly. To do that, the room has been considered as a complex system composed of several kinds of elements, such as, walls, windows and the HVAC system between others. Furthermore, it must be taken into account the outside environmental conditions, like the region climate and the adjacent rooms. After that, the relation among the different components and the adjacent environment has been established using heat transfer (conduction, convection and radiation) and mass transfer laws [16].

In this work, the room climate model is composed by eight submodels which describe the indoor air temperature, the indoor air relative humidity and six plane radiant temperatures (the surroundings walls, floor and ceil) dynamic behaviour. Hence, in can be represented by a system of differential equations given by (3).

$$\frac{dX}{dt} = f(X, U, D, V, C, t) \quad with\ X(t_i) = X_i \qquad (3)$$

where $X \in \mathbb{R}^8$, $U \in \mathbb{R}$, $D \in \mathbb{R}^7$, V and C are vectors of state variables, input variables, disturbances, system variables and constants, respectively, t is the time, X_i is the known initial state at the initial time t_i, and f is a non-linear function based on mass and heat transfer balances.

Due to the lack of space it is not possible to include a detailed description of the complete room model Thus, the interested reader is referred to [16]. Instead, a brief description of the balance equations for the indoor air temperature are displayed in (4).

$$\begin{aligned} m_a Cp_a \frac{dT_{air}}{dt} &= Q_{conv} + Q_{wind} + Q_{HVAC}\\ &+ Q_{natvent} + Q_{inf} + Q_{intGain} \qquad (4) \end{aligned}$$

where

- Q_{conv}: heat gain by free convection through walls $[W]$.
- Q_{wind}: heat gain through the window $[W]$.
- Q_{HVAC}: heat gain by forced ventilation $[W]$.
- $Q_{natvent}$: heat gain by natural ventilation $[W]$.
- Q_{inf}: heat gain due to infiltrations $[W]$.
- $Q_{intGain}$: heat gain due to internal gains (people, electrical appliances, lights, etc.) $[W]$.

The thermal comfort control (PMV) will be performed through the indoor air temperature (T_{air}) control. This variable will be controlled by means of the air temperature in the fancoil impulse (T_{imp} in $[K]$), which, at the same time, is directly controlled by the fancoil velocity [%]. One of the main disturbance in the temperature control system is the people inside the room (N_p), since it entails the increment of sensible heat as a function of the people's physical activity.

[1]Research centre on solar energy (http://www.ciesol.es), which is a mixed centre between CIEMAT and the University of Almería, located inside the Campus of the University of Almería, in the South East of Spain

It is very common to take this increment as a constant value [13]. However, each time a person goes into the room causes abrupt changes in indoor air temperature. To address this situation, each person has been considered as a heat source, which provides heat to the environment by means of three processes: respiration, evaporation through the skin and heat storage into the human body. Hence, the heat exchange between a person and his surrounding environment, Q_{person}, is modeled as follows:

$$\begin{aligned} Q_{person} &= f_{cl}hc_{cl}(T_{cl} - T_{air}) + f_{cl}hr_{cl}(T_{cl} - T_{mr}) \\ &+ 0.0014M(32 - (T_{air} - 273.15)) \\ &+ 1.7210^{-5}M(5867 - p_a) \end{aligned} \tag{5}$$

where hc_{cl} and hr_{cl} are the coefficients of heat transfer through the clothes by convection and radiation, respectively. Both in $[\mathrm{W}/(\mathrm{m}^2\mathrm{K})]$. Thus, the people's heat exchange can be calculated through (5) multiplied by the number of people inside the room, that is:

$$Q_{people} = Q_{person}N_p \tag{6}$$

IV. REPETITIVE CONTROL BASICS

Repetitive control bases its performance on the introduction of a generator of the periodic signal to be tracked/rejected inside the controller. Figure 1 shows the scheme of these generators. They are usually constructed by the feedback connection (either positive or negative, i.e. $\sigma = 1$ or $\sigma = -1$, respectively), of a time delay $W(z)$, in series with a low-pass filter $H(z)$ that reduces the gain at high frequency and improves closed-loop robustness. This yielding the generic internal model

$$I(z) = \frac{\sigma W(z)H(z)}{1 - \sigma W(z)H(z)}. \tag{7}$$

The time delay is directly related with the period of the signal. It is worth mentioning that the original internal model was constructed using $W(z) = z^{-N}$, N being the discrete time period of the signal to be tracked/rejected, $H(z) = 1$ and $\sigma = 1$.

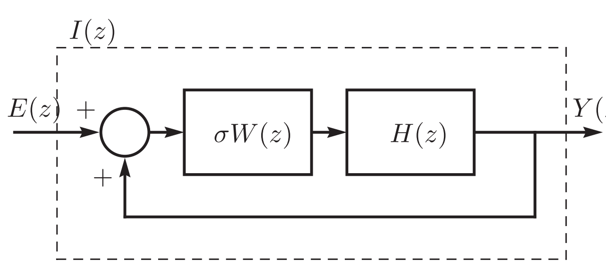

Fig. 1. Generic repetitive control internal model scheme, where $W(z)$ is a delay function, $H(z)$ a null-phase low pass filter, and $\sigma \in \{-1, 1\}$.

Besides the internal model, which assures steady state performance, repetitive controllers include a stabilizing controller, $G_x(z)$, which assures closed-loop stability. Traditionally, repetitive controllers are implemented in a "plug-in" fashion, i.e. the repetitive compensator is used to augment an existing nominal controller $G_c(z)$, as depicted in Figure 2. This nominal compensator is designed to stabilize the plant, $G_p(z)$, and provides disturbance attenuation across a broad frequency spectrum.

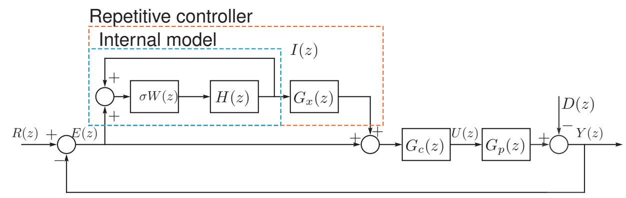

Fig. 2. Block-diagram of the repetitive controller plug-in approach.

Theorem 1: [17] The closed-loop system of Figure 2 is stable if the following sufficient conditions are fulfilled:

1) The closed loop system without the repetitive controller is stable, i.e. $T_o(z) = G_c(z)G_p(z)/(1 + G_c(z)G_p(z))$ is stable.
2) $\| W(z)H(z)(1 - T_o(z)G_x(z)) \|_\infty < 1$, where $H(z)$ and $G_x(z)$ must be selected to meet this condition.

V. SIMULATION RESULTS

To analyze the behaviour of the proposed control strategy, a simulation test of 22 days long has been performed. Furthermore, the non-periodic disturbances (the water flow of the fancoil, the inlet water temperature of the fancoil, the outdoor temperature, the solar irradiation, etc.) are taken from real data saved with the sensors network of the CDdI-CIESOL-ARFRISOL building, except for radiant temperatures and the indoor air relative humidity, which dynamics are modelled as pointed out in Section III. Whereas, the periodic disturbances are simulated following a typical office schedule. Usually people each day follow approximately the same time schedule. As a consequence, people get in/out from the room at the same time, similarly computers are turned on/off at regular time. Both people and computers can be modeled as heat sources which are turn on/off at similar times along the day. A regular timetable could be the following:

- 7:30 a.m: 7 people arrive at office and switch on 5 computers.
- 9:00 a.m: 3 people arrive at the office and switch on 2 computers.
- 2:00 p.m: Everybody leaves the office to have lunch, also all computers are turned off.
- 3:00 p.m: Everybody returns and the 7 computers are switched on again.
- 8:00 p.m: The end of working day, everybody returns home and all computers are switched off.

From this behavior and applying the equation (6) the profile shown in Fig. 3 is obtained. In the top graph of Fig. 3, the evolution of Q_{people} through the whole simulation is depicted whereas in the bottom graph a three days period zoom is shown.

Notice that, although the people inside the room is a periodic disturbance (brown solid line in Fig. 3), the effect caused by them in the indoor air temperature, i.e. the heat that the people exchange with the indoor air (magenta solid line in the top graph), is not. It is quasiperiodic. This fact is because the people's heat depends on several factors as the indoor air temperature (T_{air}), the partial water vapor pressure in the air (p_a) and the clothing surface temperature (T_{cl}), to name a few, see (5).

In order to tune the controller a simplify model has experimentally been obtained, this model relates the PMV index with the fancoil velocity (fv):

$$\frac{PMV(s)}{FV(s)} = \frac{-0.414}{271s+1}. \tag{8}$$

A sampling time of 1 minute has been selected ($T_s = 1\ min$). First of all a PI controller has been designed for the system ($k_p = -7.2464$, $k_i = 0.0037$), this controller has been tuned applying a trade-off between robustness and time response.

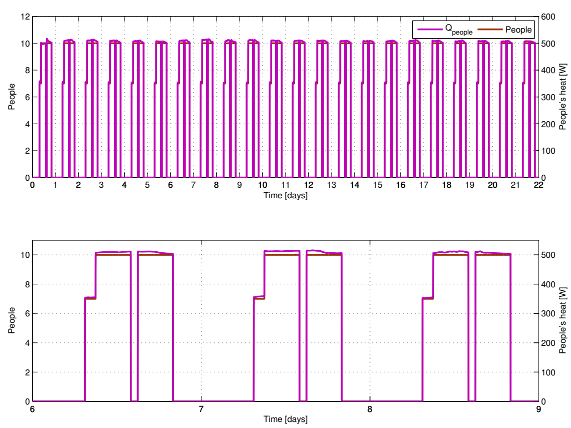

Fig. 3. Q_{people}, magenta solid line, and people, brown solid line, through a regular day.

Figure 4 shows the results obtained when using the PI controller to regulate the PMV to 0. As it can be seen the PI controller cannot avoid the oscillation over the PMV profile, indirectly these oscillation induce oscillations over other related variables like H_r.

In order to improve obtained results a repetitive controller is introduced to complement the PI controller. As it is assumed that the Q_{people} profile is repeated from day to day $N = 60min/h \times 24h/day = 1440$, as a consequence $W(z) = z^{-1440}$ and $\sigma = 1$ are selected. In this work, previous PI controller plays the role and $G_c(z)$ in Fig. 2. Combining $G_c(z)$ and the plant model the complementary sensitivity function is build, T_o, and fixing $kr = 0.9$ the

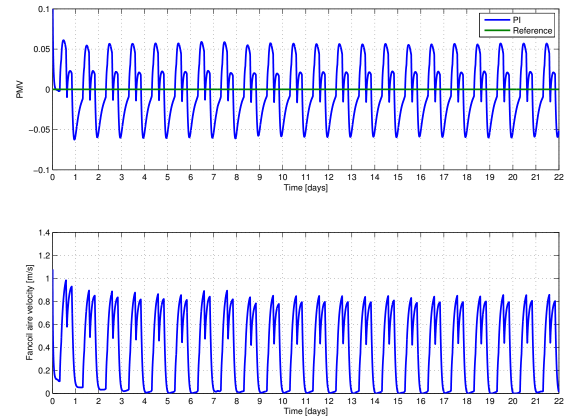

Fig. 4. Simulation results for a control system formed by PI (blue solid line). Optimal thermal comfort, $PMV = 0$, green solid line.

following stabilizing filter is obtained:

$$G_x = \frac{0.9z^2 - 1.787z + 0.8868}{0.01101z - 0.01097}.$$

Finally the low-space filter :

$$H(z) = 0.25z + 0.5 + 0.25z^-1$$

is introduced in order to improve the system robustness. In order to avoid the PI transient behavior to be propagated in future days, the first 300 min, the RC controller is not fed with the error between the setpoint and the system output, but with a 0 value.

The same scenario used in the PI simulation has also been used to evaluate the repetitive controller. Simulation results are showed in Fig. 5. As the reader can check, the results obtained when an RC controller is included in the control system are much better than the ones achieved when a single PI controller is considered. Notice that for the first day, both controllers have the same results, due to the time delay $W(z)$ of the RC. For the rest of the simulation, the control system with the RC can maintain almost an optimal thermal comfort, whereas the response of the control system with the single PI has undesirable transients, which are caused by the people that come in and out of the room. It is important to highlight that, at the beginning of the simulation, the PMV value if far from the optimum, thus, there is a transient until the optimal thermal comfort is reached.

Figure 6 depicts some of the states and non-periodic disturbances of the model. The top graph shows some of the non-periodic disturbances, the output temperature, orange solid line, and the return fancoil temperature, grey solid line. The bottom graph shows some of the model states, the air relative humidity and the mean radiant temperature. Specifically, in the right y axis, the air relative humidity (H_r): light blue solid line for the single PI controller and light red solid line for the PI plus the RC. In the left y axis, the mean radiant temperature (T_{mr}) is depicted: blue

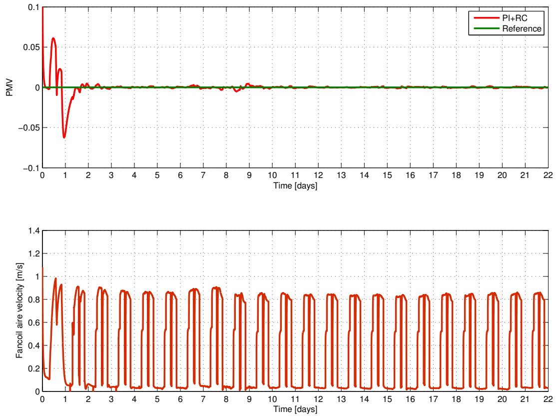

Fig. 5. Simulation results for a control system formed by PI plus RC (red solid line). Optimal thermal comfort, $PMV = 0$, green solid line.

solid line for the single PI controller and red solid line for the PI plus the RC. The variables of each tested control system have a different behaviour, mainly due to the control signal, the fancoil velocity, has influence in both variables. For the control system formed by the PI plus the RC, which reaches almost an optimal thermal comfort during most of the simulation, both variables are maintained almost constant. The obtained improvement with regard to the single PI controller is noticeable.

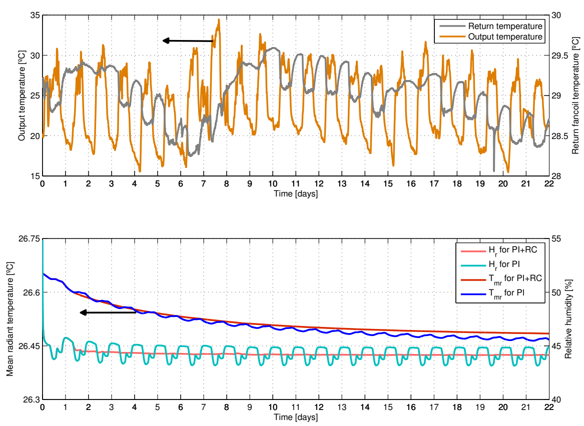

Fig. 6. Simulation non-periodic disturbances and model states. Top graph: non-periodic disturbances. Bottom graph: model states

VI. CONCLUSIONS

Control of people thermal comfort inside buildings is a topic that is receiving great attention by companies and from a scientific and technical point of view. However, the influence of the own people in the thermal comfort is not usually taken into account. Since such an influence has a periodic pattern in the cases of offices or laboratories, where the timetable is the same day after day, the people effects can be considered as a periodic disturbance. This work proposes the use of an RC controller in order to counteract this periodic disturbance.

To test the proposed control strategy, simulation results are presented. These simulation results are obtained from a nonlinear model based on first principles that represents the thermal behaviour of the more representative room of the CDdI-CIESOL-ARFRISOL building. The results show an improvement in the thermal comfort when the RC controller is included. Additionally, it has been determined that this control strategy is able to maintain thermal comfort even when people is coming in and out of the room. Future work is aimed to perform real tests with this approach inside the CDdI-CIESOL-ARFRISOL building in order to obtain the same promising results than in simulation.

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