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Tuning of PID Controllers for Air Conditioning System

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Abstract

This paper describes a tuning for PID controller based on a trial and error method. The algorithm is applied to a computer based single-input single-output (SISO) on air conditioning (AC). Some experiments are conducted to observe the ability of the controller in the temperature control of SISO AC under set-point changes. The controller gains to obtain a good response of the room temperature and optimum energy consumption for the system studied were found to be 3.3, 0.180 and 0.040 for the proportional, integral and derivative terms, respectively. The experimental results prove that the controller is capable of giving a good control result for the process.

Keyword*: PID control, tuning, variable speed, air conditioning.*

1. Introduction

There are many types of controller that have been developed, among others are classical control (such as : On/Off or PID) and intelligent control (such as : fuzzy logic, expert system, neural network, etc.). Each controller method has its own advantages and limitations, some methods are often combined with another to provide better performance.

Design and implementation of a control system require the use of efficient techniques that provide simple and practical solutions in order to fulfil the performance requirements in the presence of the disturbance and uncertainties in the system (Reznik *et al*., 2000). The design method should enable full flexibility in the modification of the control surface to obtain significant improvements (Kowalska *et al*., 2002). Linear control techniques with a long history of successful industrial applications are valid for small ranges of operation for linear models. Modern industrial units require increased flexibility, and this results in nonlinear behavior of partly unknown systems (Eker and Torun, 2006).

The response of a nonlinear system, generally, cannot be shaped to a desired pattern using a linear controller. Nonlinearities are difficult to realize with conventional model based linear controller such as PID controllers, and many additional measures such as unit-reset windup, retarded integral action etc. should be included for proper functioning of the controller. The systems involved in practice are, in general, complex and time variant, with delays and nonlinearity and often with poorly defined dynamics (Eker and Torun, 2006). When a system becomes too complex to be described by analytical models, it is unlikely to be efficiently controlled by conventional approaches. In this case, conventional control methodology can simplify the system model but not provide good performance. As a result, many PID controllers have been poorly tuned (Reznik *et al*., 2000). Moreover, design of conventional PID controllers is based on long duration experience and many experiments. In addition, conventional control methods have not been very much involved in solving higher level control problems such as supervision, optimization, monitoring, planning and scheduling of dynamic complex systems. Consequently, nonlinear controllers are required to control such systems satisfactorily (Eker and Torun, 2006).

Tuning of the PID controllers is achieved in two steps. In the first step a simplified model of the process is obtained and initial tunings are calculated using well-known tuning rules (such as the modified Ziegler-Nichols (ZN) or Internal model control (IMC) based). In the second step, the performance of the loop is assessed and the initial tunings are modified in order to take into account the operating specifications of the process. The success or failure of this procedure strongly depends on the judicious choice of initial tunings. However, all available tuning methods have been developed to satisfy specific design objectives which, in most cases, cannot be translated into the design objectives of a specific application. Thus, control engineers often face the need to develop customized tuning rules that speed up the controller tuning procedure by minimizing the time needed for tuning or even eliminating retuning (Syrcos and Kookos, 2005).

There are several recommendation for tuning PID controller parameters and for experimental determination of process characteristics to obtain process variable which will be used to set controller parameters. These procedures can be applied when mathematical model of the process is known and also when it is unknown. In any case, these recommendations can be used for initial tuning of the controller and then user can perform fine tuning using more detail knowledge of the process. The most often used recommendations are ZN, Cohen-Coon (CC), IMC and the trial and error (TEA) , with have advantages and disadvantages.

This paper is focused on PID controllers tuning. The main idea of designing the controller is to maximize energy saving and thermal comfort for an air conditioning (AC) system application.

2. Algorithm

The PID controller algorithm is the almost universally used control strategy. The PID control equation is defined by (Perdikaris, 1998) :

$$u(t) = K_p e(t) + K_i \int e(t)dt + K_d \frac{de(t)}{dt} \qquad \ldots\ldots\ldots\ldots\ldots \qquad (1)$$

The use of proportional control (P) requires just one variable to be selected, the proportional gain K_p, for the control system to satisfy the required dynamic behavior. The use of a proportional plus integral gains (PI) or proportional plus derivative gains (PD) controller requires the selection of two variables, K_p and K_i or K_p and K_d, respectively. With a PID controller three variables have to be selected: K_p, K_i and K_d. For a digital PID controller (Perdikaris, 1998) the controller gains K_P, K_I and K_D can be determine from the analog controller gains using the following relationships:

$$K_P = K_p$$

$$K_I = K_i \times \Delta t$$

$$K_D = K_d / \Delta t$$

where Δt is the sampling time (minute).

The output of the digital controller can be expressed by:

$$u_P(t) = (K_P \times e(t)) \qquad \ldots\ldots\ldots\ldots\ldots \qquad (2)$$

$$u_{PI}(t) = [K_P \times e(t)] + [K_I \times (\sum_{i=1}^{n} e(t-i) \times \Delta t)] \qquad \ldots\ldots\ldots\ldots\ldots \qquad (3)$$

$$u_{PD}(t) = [K_P \times e(t)] + \left[K_D \times \left(\frac{\Delta e(t)}{\Delta t}\right)\right] \qquad \ldots\ldots\ldots\ldots\ldots \qquad (4)$$

$$u_{PID}(t) = [K_P \times e(t)] + [K_I \times (\sum_{i=1}^{n} e(t) \times \Delta t)] + \left[K_D \times \left(\frac{\Delta e(t)}{\Delta t}\right)\right] \qquad \ldots\ldots\ldots\ldots\ldots \qquad (5)$$

where

e (*t*) = *setpoint temperature* (*t*) – *measured temperature* (*t*)

$\Delta e = e(t) - e(t-1)$

3. Tuning Method

The PID parameters K_p, K_i, and K_d need to be adjusted for optimum system performance and this process is called tuning. Controller tuning means the process of adjusting the controller parameter of the proportional action, integral action and derivative action to achieve the desired system performance.

The basic principle of tuning is to set the time and controller parameters of the controller to fit the time and parameters (called dynamics) of the process. When tuning, generally it is necessary to upset the process (Clair and Fruehauf, 1994). For controller tuning, simplicity, as well as optimality, is important. The three modes of the ordinary PID controller, K_p, K_i, and K_d do not readily translate into the desired performance and robustness characteristics which the control system designer has in mind. The presence of simple rule which relate model parameters and/or experimental data to controller parameters serves to simplify the task of the designer (Rivera *et al.*, 1986).

For the last 60 years, several methods for detemining the PID controller parameters have been developed. O'Dwyer (2003a) reported the sources of tuning rules published in the journal acticles, conference papers, books and theses amount to 207 publications and 381 equations over a period of 1942 to 2002. Some of them deal with some kind of optimal approach. Actually, the development of PID tuning rules has been one of the major areas of research about PID controller. Twenty six structures have been considered. The labelling of these structures and terms has not been consistent in the literature. For example : stability analysis method, synthesis method, constant open loop transfer function method, pole placement method, internal model controller method, optimization method and two degree of freedom method (Sree *et al*., 2004), analytic methods, heuristic methods, frequency response methods, optimization methods, and adaptive tuning methods (Ang *et al*., 2005; Li *et al*., 2006), process reaction curve methods, optimum regulator or optimum servo action methods, direct synthesis methods, robust methods, ultimate cycling methods and other methods : performance index minimization (O'Dwyer, 2003a), model free methods, non-parametric model methods and parametric model methods (Moradi, 2003), first order lag plus delay (FOLPD) model, integral plus delay (IPD) model, and stable or unstable second order system plus delay (SOSPD) model (O'Dwyer, 2003b), simple almost optimal tuning rules, skogestad internal model control (SIMC), traditional parameter choice, Kristiansson-Lennartson method, Ziegler-Nichols method, and Astrom-Hagglung method (Kristiansson and Lennartson, 2006), the integral square error (ISE) method, the iterative feedback tuning (IFT) method and virtual reference feedback tuning (VRFT) method (Lequin *et al*., 2003), empirical methods and methods based on optimization (Herrero *et al*., 2002), direct and indirect tuning methods (Vrancic *et al*., 1999), closed loop method only, simplified IMC-PID tuning rules and Bekker *et al*. tuning rules (Jette *et al*., 1998), Ziegler-Nichols step response method, the Cohen-Coon method, Lambda tuning, and the Kappa-Tau methods (Hagglund and Astrom, 2002), original IMC-PID tuning rules, Astrom/Schei PID tuning, Ziegler-Nichols (ZN) PID tuning rules and Tyreus-Luyben modified ZN PI tuning rules (Skogestad, 2003), multivariable tuning methods (Katebi *et al*., 2000) and trial-and-error (Krakow *et al*., 1995; Nesler, 1986; Ho, 1993; McGowan *et al*., 2003).

3.1. Trial-and-Error Tuning Method

The most basic method of tuning is the trial and error (TAE) method. In the TAE tuning method, the operator's experience is combined with a step-by-step procedure to experimentally determine the appropriate controller parameters. Without an established procedure, controller tuning can be a frustrating experience due to the interaction of the tuning parameters (Stoecker and Stoecker, 1989). This method involves adjusting the controller parameters until the performance is satisfactory. Having a set of guidelines to do this, the task of arriving at a set of controller gains is much easier. The following is a six-step set of rules that can make tuning a PID controller much easier (Seborg *et al*., 1989).

Step 1. Eliminate integral and derivative terms. Leaving a proportional only controller.
Step 2. Set the proportional gain (K_p) to a small value and start the process.
Step 3. Gradually increase K_p until oscillations are sustained with a corresponding step change in the setpoint.
Step 4. Reduce K_p by a factor of two.
Step 5. Gradually decrease K_i until sustained oscillations result with a step change in the setpoint. Set K_i equal to three times this value.
Step 6. Increase K_d until sustained oscillations result with a step change in the setpoint. Set K_d equal to one-third of this value.

Steps 1 to 3 are similar to the ZN tuning using frequency response method. The disadvantages of the trial and error method is time consuming if a large number of trials are required in order to find the controller parameters. This tuning method is not applicable to processes that are open-loop unstable because such processes typically are unstable at both high and low value of K_p, but are stable for an intermediate range of values (Seborg *et al*., 1989).

3.2. The Proposed Tuning Method

Tuning of the PID controllers is achieved in two steps. In the first step a simplified model of the process is obtained and initial tunings are calculated using well-known tuning rules (such as the modified ZN or IMC based). In the second step, the performance of the loop is assessed and the initial tunings are modified in order to take into account the operating specifications of the process. The success or failure of this procedure strongly depends on the judicious choice of initial tunings. However, all available tuning methods have been developed to satisfy specific design objectives which, in most cases, cannot be translated into the design objectives of a specific application. Thus, control engineers often face the need to develop customized tuning rules that speed up the controller tuning procedure by minimizing the time needed for tuning or even eliminating retuning (Syrcos and Kookos, 2005).

There are several recommendation for tuning PID controller parameters and for experimental determination of process characteristics to obtain process variable which will be used to set controller parameters. These procedures can be applied when mathematical model of the process is known and also when it is unknown. In any case, these recommendations can be used for initial tuning of the controller and then user can perform fine tuning using more detail knowledge of the process. The most often used recommendations are ZN, CC, IMC and TEA, with have advantages and disadvantages.

The ZN step response method is an experimental open-loop tuning method and is only applicable to open-loop stable plant (Silva *et al*., 2005). While the CC and IMC methods are based on model of the plant for closed-loop tuning method. The ZN step response, CC and IMC are not applicable for tuning method in this research. Further, the ZN frequency response method is a closed-loop tuning method. With this procedure no process model is assumed. The procedure is based on measurements only. This tuning method is not often applied in practice because it is laborious and time consuming, particularly for a process with large time constant (Hang *et al*., 1991). Adjusting the parameters of the controller by trial and error to obtain acceptable performance (Seborg *et al*., 1989; Gopal, 2002) and the model parameter calculations are more complicated than the standard open-loop method (Seborg *et al*., 1989). Also the ZN frequency response tuning procedure (such as Step 1 and 2) is similar with TAE.

A typical approach for tuning a PID controller can be summarized as follows

Step 1. Eliminate integral and derivative terms. Leaving a proportional term only.
Step 2. Set the values of K_p from 0 to 3.3. Decrease K_p by small decrement.
Step 3. Observe the output room temperature and compute the energy consumption.

Step 4. If the output room temperature approaches the setpoint temperature and meet the energy consumption requirement go to Step 5, else repeat Step 2 and 3.
Step 5. Switch off the derivative mode to zero to tune PI controller.
Step 6. Set the value of K_i from 0.065 to 0.495 and K_p to toned value (as in Step 2). Decrease K_i by small decrement.
Step 7. Observe the output room temperature and compute the energy consumption.
Step 8. If the output room temperature approaches the setpoint temperature and meet the energy consumption requirement go to Step 9, else repeat Step 6 and 7.
Step 9. Eliminate integral action from the PID algorithm for tuning PD controller.
Step 10. Set the value of K_d from 0.001 to 0.040 and K_p to the tuned value (as in Step 2). Decrease the K_d by small decrement.
Step 11. Observe the output room temperature and compute the energy consumption.
Step 12. If the output room temperature approaches the setpoint temperature and meet the energy consumption requirement go to Step 13, else repeat Step 10 and 11.
Step 13. Set the tuned value of K_p, K_i and K_d for PID controller.

The tuned PID controller parameters are given in Table 1. The determination of optimum value of all controller parameters (K_p, K_i and K_d) was done by a TAE basis. The optimized controller parameters enable the room temperature to approach the reference temperature and the energy consumption is minimized. The controller parameters were chosen in this research as shown in Table 1. The tuned value of controller parameters could be used for various temperature setting and internal heat loads.

Table 1. The tuned PID controller parameters

	K_p	K_i	K_d
Trials	2.0 to 3.3	0.065 to 0.495	0.001 to 0.040
Tuned	3.3	0.180	0.040

4. Experimental Setup

Figure 1 shows the points of measurement for temperature and pressure represented by T and P. Points T_1 and T_2: input and output temperatures at compressor, T_3 and T_4: input and output temperatures at condenser, T_5 and T_6: input and output temperatures at evaporator, and T_7-T_{11} are measurements for the room temperature. Points P_1 and P_2: input and output pressures at compressor, P_3 input pressure at condenser, and P_4 input pressure at expansion valve. Temperatures were measured by T type thermocouple and ICs temperature sensors. Pressures were obtained using Bourdon type gauges. Those locations on the high-pressure side ranged from 0 to 30 bar by 1 bar scales. The low-pressure side ranged from 0 to 10 bar by 0.2 bar scales. Electrical energy consumption was measured from the motor through PCI-1711/PCLD-8710 interface to the computer. Analog filter was used to separate the desired signals from unwanted interference or noise. The experiments were conducted with 22^{o}C and the values of K_p = 2.0 to 3.3, K_i = 0.065 to 0.495, and K_d = 0.001 to 0.040 were used.

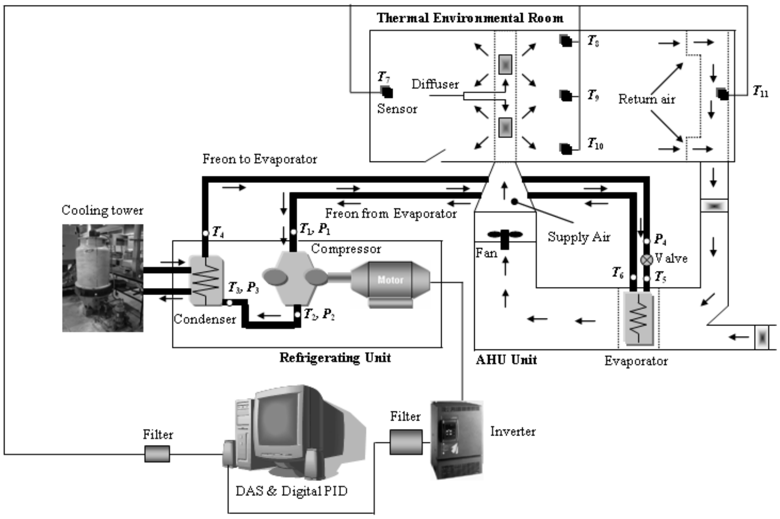

Figure 1. The experimental setup

5. Results and Discussion

The motor speed and temperature response and the steady state value of room temperature are given in Figures 2-4 for K_p, K_i and K_d, respectively. The value of K_p, K_i and K_d provide more sensitive response to the room temperature and energy consumption. With a higher K_p and K_d values then the smaller is energy consumption and temperature oscillation. The results indicate that the energy consumption increases when the error is higher between the reference and the room temperature, and vice versa. Referring to the temperature setting, the controller tries to minimize the error between the reference and the room temperatures. The controller is to control the rotational speed of the compressor as to maintain the room temperature at or close to its temperature setting.

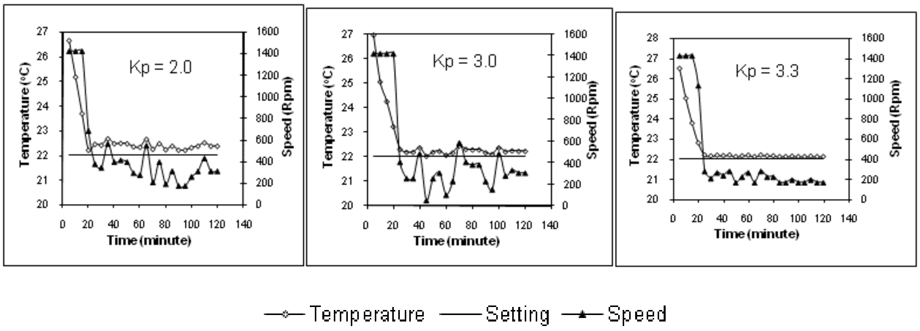

Figure 2. Motor speed and temperature responses at various K_p

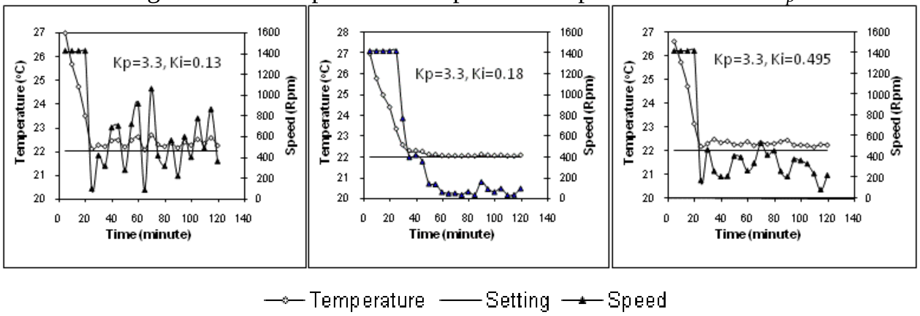

Figure 3. Motor speed and temperature responses at various K_i

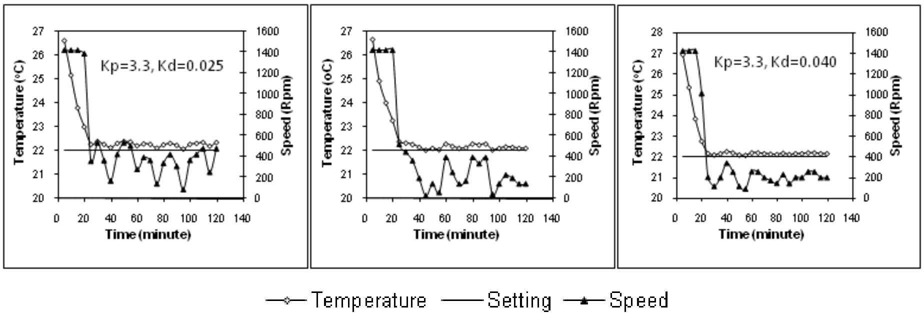

Figure 4. Motor speed and temperature responses at various K_d

6. Conclusion

The problem with designing a PID controller, is selecting the values for the PID parameters i.e. K_p, K_i and K_d. When the plant is unknown, the PID design problem is essentially one of trial and error, and it becomes increasingly more difficult in the presence of large dynamic interactions, nonlinearities and parameter variation in the plant. In particular, the PID controller parameters must be continuously adjusted (or tuned) in order to meet the performance criteria.

The PID controller tries to minimize the error between the setpoint temperature and the room temperature. If the room temperature reaches the setpoint, the motor speed is abruptly reduced and will fluctuate to maintain the room temperature. However, when the room is thermal loaded, the controllers act such that the heat recovery to the room is faster until the temperature setpoint is upheld again. The speed variation for the controlled system was found to be between 0 to 500 rpm.

A well-tuned PID controller that produced satisfactory solution in term of energy saving for the room was employed. The tuned PID controller parameters under investigation was found to be $K_p = 3.3$, $K_i = 0.180$ and $K_d = 0.040$. The impacts of all controllers on the performance of the system, the room temperature and energy consumption have been analyzed experimentally using variable speed motor compressor. The main outcome of this study shows that using variable speed compressor and choosing suitable control strategy, it is capable to control the space temperatures with significant energy saving.

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