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Online H_∞ adaptive tuning of PI controllers for discharge air temperature system

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ABSTRACT

The problem of online adaptive tuning of PI controllers in heating, ventilating and air conditioning (HVAC) systems is explored. A discharge air temperature (DAT) system is described by a first-order plus dead-time model. The model parameters were estimated online while the control remains in the closed-loop. H_∞ adaptive tuning rules were applied and new PI parameters were estimated. Both computer simulations and experimental responses were studied. The results show that the H_∞ adaptive PI (HIAPI) controller is able to track set-point changes, reject the effects of multiple disturbances and is robust to changes in model parameters.

1. DAT systems

The discharge air temperature (DAT) system is one of the basic sub-system in heating, ventilating and air conditioning (HVAC) systems. The discharge air temperature in a typical DAT system is maintained by controlling the chilled-water flow rate through a cooling coil. The chilled-water flow rate is changed by modulating a flow control valve. Warm air enters the cooling coil and is cooled and dehumidified as it leaves the cooling coil.

Because of the variability of the operating conditions, such as, changes in supply air temperature, airflow rate and chilled water supply temperature, a constant-gain PID controller cannot satisfy the requirement of tracking set-point changes very well under variable load conditions. Under these circumstances, an adaptive regulator which can change its behaviour in response to changes in the dynamics of the process and the disturbances is a preferred option [1]. Also, there are a number of apparent advantages in using adaptive controls in HVAC applications. Commissioning costs would be less since the commissioning period would be shorter. Noting that direct digital PID controllers are already familiar to engineers in the HVAC field, it is of interest to develop online adaptive tuning methods to update the PID parameters. Motivated by these considerations, we are interested in exploring the design of adaptive PI controller with self-tuning capabilities for a DAT system.

The discharge air temperature (DAT) system must be designed and operated to maintain dynamic equilibrium between the zone thermal loads and plant heat extraction rates. Because of its impact on occupants' comfort, equipment performance and operating costs, the DAT control problem is a challenging research problem with the potential for significant economic benefits. Several authors have studied the controller design methods which include both classical and more advanced design methods. In the following a critical review of the PID design and tuning methods for HVAC systems is presented.

Seem [2] presented a method for implementing a new pattern recognition adaptive controller (PRAC) developed through optimization, for automatically adjusting the parameters of PI controllers. Depending on patterns of the closed loop response, PRAC determines the parameters of the digital PI controller used in a HVAC system. Simulation results subject to random noise and load disturbance are presented. Some field test results are also given. The results showed that PRAC is robust, easy to use and has low computational and memory requirements. From the results presented, it was noted that PRAC responses are somewhat sluggish or oscillatory and take long time to reach stable state. The limitation is that PRAC was developed for first-order plus dead-time systems with the ratio of dead time to time constant between 0.25 and 1, and the ratio of sampling time to time constant between 0.1 and 1 for "good control."

Dexter [3] and Dexter and Haves [5] developed a robust self-tuning predictive controller based on the generalized predictive control algorithm [4] for HVAC applications. The controller uses default values for most of its parameters and requires selection of only one commissioning parameter: the control-sampling interval. In the controller, a parameter estimator based on the UD filter form of the recursive least-squares algorithm [5] is used. To implement a

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set of expert rules, which supervise the operation of the on-line parameter estimator and the calculation of control action, Dexter and Haves [5] developed a special jacketing software. They have used a component-based computer simulation package (HVAC-SIM+) to examine the behaviour of the controller in both the zone and supply air temperature control loops. The robust behaviour of the self-tuning controller is presented and its superior performance to that of a manually tuned PI controller is demonstrated through simulation results. Application of the self-tuning controller in a cascaded control configuration is also discussed and they concluded that the use of two self-tuning controllers within a cascaded control scheme worked well when care was taken to deal with the interactions that occurred between the inner and outer loops during the tuning period. Although the control strategy has some merits, the controller is too complex for implementation on existing building control hardware. Also the accuracy of the estimator over extended period of operation is not proven in the study.

Kasahara et al. [6] have developed a design and tuning method in which the gains of a robust PID controller for HVAC systems are obtained by solving a two-disk type mixed sensitivity problem. The PID gains obtained by the conventional Ziegler–Nichols rules were modified by applying this technique. To illustrate the method, the temperature control of a single-zone environmental space and the HVAC plant which was approximated by a first-order lag plus dead-time system was considered. The numerical simulation and the experiments on a commercial-size air conditioning plant were conducted. The results showed that smaller PID gains resulted in better robustness compared to the Ziegler–Nichols rules. The study showed that the robust PID gains could be expressed as simple linear functions of the ratio of the dead-time to the time constant. However, for every plant, the use of this method requires the determination of six parameters off-line to compute the three gain reduction factors.

Krakow [7] has proposed the relationship between the sampling interval and digital PI control system performance by using experimental and simulated response characteristics of a PI-controlled mixing valve air heating system. The PI tuning rules were proposed based on the analytical and experimental study by Krakow et al. [8] and Hussein [9] for the first-order system (without storage) and second-order system (with storage). The authors concluded that, long sampling intervals may yield more satisfactory response characteristics, than short sampling intervals if the system is tuned appropriately. Appropriate tuning implies using PI coefficients based on (non-conventional) theory developed specifically for long sampling intervals. The limitation of the paper is that the results obtained are specific to a system and cannot be generalized and readily implemented on real-time HVAC control loops.

Nesler [10] presented the implementation of a self-tuning controller to control typical HVAC processes (the model was considered as a first-order plus dead-time). The self-tuning controller consisted of five independent software blocks: an automatic tuning routine used to establish initial parameter estimates, a recursive least-squares estimator for making parameter estimates on-line, a controller design block, which computes the gains of PI controller depending on the new parameter estimates, a PI controller, and a performance monitor, which supervises the self-tuning controller operation. The open-loop step test method is used for the automatic tuning routine. The PI gains are computed by minimizing the integrated absolute error (IAE). In addition, a performance monitor was introduced to determine when retuning is required. The use of the performance monitor can also increase system flexibility and robustness. The main limitation of recursive least squares (RLS) estimation is that self-tuners can produce faulty estimates whenever large and un-modeled load disturbances occur as in HVAC processes. In addition, the robustness of self-tuning control was not demonstrated.

Huang and Lam [11] presented an adaptive learning strategy based on genetic algorithm (GA) for automatic tuning of PID controllers in HVAC systems to achieve optimal performance. The simulation results show that this algorithm is useful for automatic tuning of PID controllers for HVAC systems, yielding minimum overshoot and settling time. An optimal PI controller-tuning program based on genetic algorithm was developed and implemented in a non-linear HVAC system. The results obtained show that the GA method yields better performance than that of the traditional Ziegler–Nichols method for controller tuning. Experimental work is needed to verify the accuracy of such methods.

Chen and Lee [12] developed an adaptive robust controller for a single-zone HVAC system that possesses modeling uncertainty and non-linearity. Simulation results depict a satisfactory transient performance under a significant deviation of the initial state from the comfort region. The adaptive robust control was proved by theory to guarantee stability. However, this paper only provided theoretical study and the basic framework for further experimental verification. Experimental study is necessary to validate the control performance under realistic operating conditions.

Wang et al. [13] developed a PID auto-tuner and presented its application to HVAC systems. A second order plus dead-time model is identified by the auto-tuner based on two continuous relay feedback experiments. The PID controller was designed on the basis of gain- and phase-margin specifications. The use of second-order model adds to complexity and will be difficult to implement on available building control systems.

Zaheer-uddin and Tudoroiu [14] explored the problem of improving the performance of a discharge air temperature (DAT) system using a PID controller and augmenting it with neural network based tuning and tracking functions. They modeled the DAT system as a single input single output (SISO) system, and presented the architecture of the real-time neuro-PID controller and simulation results obtained under realistic operating conditions. The results show that the network assisted PID controller is able to track both constant and variable set point trajectories efficiently in the presence of disturbances acting on the DAT system. However, this methodology is not experimentally verified. It may be difficult to implement the method on available control hardware platforms currently used in HVAC systems.

In addition to the limitations of the studies noted above, it should be pointed out that most of the previous studies have not considered the robustness property in the controller design. Another important distinction between the proposed study and the previous studies is that the discharge air system considered in this study includes zone and system dynamics representing the operating conditions much closer to a real building environment. This was achieved by conducting load disturbance experiments to test the robustness property of the proposed controller over a wide range of operating conditions than those published in the literature. To this end, the objective of this study is to develop an on-line robust adaptive tuning algorithm for PI control such that the controller is: (i) simple for implementation using available hardware; (ii) robust and adaptive to load changes; (iii) stable; (iv) fast with good set-point tracking property. Here we consider a first-order model and develop an adaptive tuning strategy for DAT control system. The major focus of this development will be that the model and the tuning strategy should be suitable for online implementation on available building control platforms.

1.1. Physical model

Fig. 1 shows a schematic diagram of a DAT system. Mixed air enters the cooling coil at temperature $Ta0$ and flow rate Q. It is cooled and dehumidified in the cooling coil by using chilled water. The temperature of the air leaving the cooling coil Ta is controlled