Field and Laboratory Results for A New Pattern Recognition Adaptive Controller

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ABSTRACT

This paper presents laboratory and field test results for a new pattern recognition adaptive controller (PRAC) that adjusts the gain and integral of proportional-integral controllers while under closed loop control. The laboratory results demonstrate how PRAC tunes a static pressure control loop with aggressive and sluggish initial conditions. Field test results are presented for a static pressure control loop, supply air temperature control with a heating coil, supply air temperature control with dampers, and supply air temperature control with a cooling coil.

PRAC is easy to use and provides near-optimal performance for a range of systems and noise levels. Also, PRAC is computationally efficient and does not have large memory requirements. Thus, PRAC can be used in today's digital control systems. Using PRAC to control HVAC processes will result in a number of economic and environmental rewards: time for commissioning new control systems will decrease, time for retuning control loops will be eliminated, actuator life will increase, energy use will decrease, and indoor air quality and the safety of building occupants will improve. PRAC has successfully tuned control systems for heating, ventilating, and air-conditioning equipment in office buildings, high schools, universities, national laboratories, department stores, hospitals, clinics, and large sports stadiums.

INTRODUCTION

In the HVAC industry, we use feedback controllers to maintain temperature, humidity, pressure, and flow rates for HVAC equipment. According to Åström and Hägglund (1988), most feedback loops are controlled with proportional-integral-derivative control algorithms. For HVAC applications, derivative action is normally not justified (CIBSE, 1985). Haines (1988) said the preferred method of control for HVAC applications is proportional plus integral (PI) control because of improvements in accuracy and energy consumption when compared to proportional control. Following is a "textbook" version of an analog PI control algorithm

$$u(t) = K\left(e(t) + \frac{1}{T_i}\int_0^t e(\tau)\,d\tau \right) \tag{1}$$

where $u(t)$ is the controller output at time t, K is the controller gain, $e(t)$is the error at time t, and T_i is the integral time. In the controls industry, the process of determining proper values for the control parameters is commonly called tuning. The control performance is dependent on the controller gain and integral time.

The HVAC industry is a cost sensitive business, and people installing and commissioning systems do not have a long time to tune loops. Consequently, some PI algorithms use the default control parameters shipped with the controller. For some systems, the default control parameters are not appropriate and using them leads to poor control performance. To maintain a safe and comfortable environment without wasting energy, it is important to have well tuned control systems. Concerning tuning of PID controllers, Åström and Hägglund (1988) said "Although PID controllers are common and well-known, they are often poorly tuned. Evidence for this can be found in the controls room of any industry."

Computer control systems can automate the tuning process. There are two basic automatic tuning methods: auto-tuning and adaptive control. With auto-tuning, the operator initiates a command to determine new control parameters and the control parameters remain constant until a new command is issued. If the system dynamics change, then the operator must initiate a new command to determine new control parameters. With adaptive control, the computer control system automatically changes the controller parameters as the system dynamics change. Several textbooks have been published on auto-tuning and adaptive control methods: Åström and Häggland (1995), Åström and Wittenmark (1995), Hang et al. (1993), Isermann (1992).

Several researchers have attempted to apply adaptive control methods to HVAC systems. Dexter and Haves (1989) and Jota and Dexter (1988) used the Generalized Predictive Control Algorithm (Clarke, et al., 1987) to control different HVAC systems. Dexter and colleagues concluded that the magnitude of the disturbances found in the HVAC industry causes problems when applying self-tuning and adaptive control methods. Also, the self-tuning controller must be significantly detuned in order to maintain reliable control over the full operating range. Detuning the self-tuning controller helps prevent the parameter estimator from determining unreliable estimates. Ling and Dexter (1994) said the amount of detuning that is required is difficult to determine. Nesler (1986) used recursive least squares (RLS) estimation in a self-tuning controller on a HVAC process. Nesler reported that unmodeled process disturbances and actuator hysteresis limited the effectiveness of the RLS self-tuner. In summary, it appears difficult to develop an adaptive controller for the HVAC industry.

Today, adaptive control is not widely used in the HVAC industry. According to MacArthur et al., (1989), adaptive controllers need the following characteristics to be widely accepted in the HVAC industry: be extremely robust, handle unmeasured load disturbances, perform with system non-linearities, be insensitive to noise, require no detailed a priori knowledge of the process, operate without supervision, require minimal operator input, and require no off-line computations.

In the future, we think adaptive control will become widely used in the HVAC industry because of the benefits associated with adaptive control. Following is a list of benefits that would result from using adaptive control in the HVAC industry:

- *Eliminate or reduce installation time for tuning new control systems.*
- *Eliminate service time for retuning existing control systems.* Many control loops require retuning during the year because a number of HVAC systems have time varying dynamics. The time varying dynamics are caused by non-linear system characteristics and time varying loads, i.e., loads for HVAC systems frequently change with the time of the day, day of the week, and season. The system dynamics may also change because of heat exchanger fouling, wear on valves, or unusual operational status, during start-up or after a component failure (Seborg et al. 1989).

- *Saves energy*. ASHRAE (1995) has graphs that shows the performance on an air handling unit controller that has oscillating control loops. The figures show the position of the outdoor air damper and steam preheat valve over a twenty-five minute period. During this time period, the preheat valve and outdoor-air damper swing open and closed every two minutes. ASHRAE said, “Clearly, such control system performance wastes energy by the unnecessary use of preheating and has a negative impact on comfort conditions ... These problems can be corrected by proper tuning of the controls ...” An adaptive control system could automatically retune the control system.

- *Longer equipment life.* Robust adaptive controllers will increase equipment life by reducing the wear associated with oscillating control loops.

- *Improved occupant comfort.* Robust adaptive control systems will improve occupants comfort by increasing control performance.

- *Improve occupants safety.* In buildings, such as laboratories or hospitals, the performance of the HVAC control system has a strong influence on the safety of building occupants. Robust adaptive control systems would improve the safety of building occupants.

Seem (1996) describes a new pattern recognition adaptive controller (PRAC) that continually tunes PI controllers. The new adaptive controller has the following features:

- *Robust.* PRAC does not detune after system or component failures. For example, if there is a sensor failure, then PRAC stops tuning. After the sensor is working properly, the control system responds well to disturbances. Also, PRAC stops tuning if the load exceeds the system capacity, or the controller is put in a manual mode of operation.

- *Easy to use.* PRAC is easy to use because the building operator has to select only one input: the type of control loop, for example, static pressure control, volume matching control, supply air temperature control with a cooling coil, supply air temperature control with a heating coil, or room temperature control.

- *Near-optimal performance.* PRAC provides near-optimal performance in terms of the integrated absolute value of the error following both setpoint changes and load disturbances.

- *Tunes both noisy and noise-frees systems.* PRAC tunes systems that are both noisy and noise free. Also, PRAC automatically adjusts to different levels of noise.

- *Tunes both sluggish and oscillatory systems.* PRAC tunes systems that are either exhibiting sluggish or oscillatory behavior.

- *Low computational and memory requirements.* The computational and memory requirements necessary to implement PRAC in a digital control system are small. Thus, PRAC can be used in low cost digital controllers, such as variable-air-volume terminal unit controllers.

The purpose of this paper is to present laboratory and field test results for PRAC. The paper is organized as follows. First, we review the method used to develop the new PRAC. Second, we provide an overview of the algorithm. Third, we present laboratory test results for static pressure control of a variable-air-volume system. Finally, we present field test results.

DESCRIPTION OF PRAC

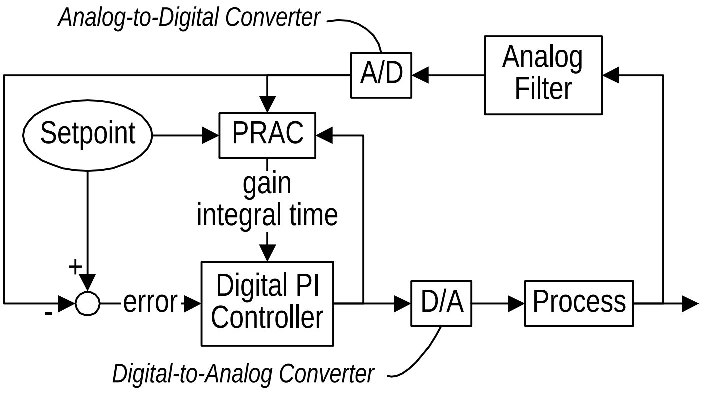

Figure 1 Block diagram that shows connections to PRAC.

PRAC determines the gain and integral time for a digital PI controller while under closed loop control. Figure 1 shows the connections between PRAC, the digital PI controller, and the process. The digital PI controller should use an anti-reset strategy to prevent the integral term in Equation 1 from taking on large values after the controller output saturates. Clark (1984), Seborg et al. (1989), and Åström and Hägglund (1995) review different anti-reset strategies. The bandwidth for the analog filter should be selected to prevent aliases from entering the digital control system. PRAC determines the gain and integral time from the sensed value for the process output, the controller output, the setpoint, and the error.

PRAC was developed for systems that can be characterized by the first-order plus dead-time model

$$G(s) = \frac{K e^{-\tau_{dead} s}}{1 + s\tau} \tag{2}$$

where

$$0.1 \le \frac{T}{\tau_{dead}} \le 1 \tag{3}$$

$$0.25 \le \frac{\tau_{dead}}{\tau} \le 1 \tag{4}$$

$G(s)$ is the Laplace transfer function, K, is the process gain, τ_{dead} is the dead time (time delay), τ is the time constant of the process, and T is the sample time for the digital PI controller. Seborg et al. (1989) and Luyben (1990) review methods for determining the dead time and the time constant from experimental data. For HVAC processes, the ratio of sampling time to dead time and the ratio of dead time to time constant are typically within the limits in Equations 3 and 4.

The internal structure of PRAC is shown in Figure 2. The five shadowed blocks represent the major steps necessary to implement PRAC. Next, we present a brief description of the five shadowed blocks. Details of the internal structure of PRAC are presented by Seem (1996).

Block 1 uses smoothing algorithms to estimate the process output and the slope of the process output. Also, this block estimates the noise level in the process output signal. The noise level estimate is used in Blocks 2 and 5.

Block 2 determines when a significant setpoint change or load disturbance has occurred.

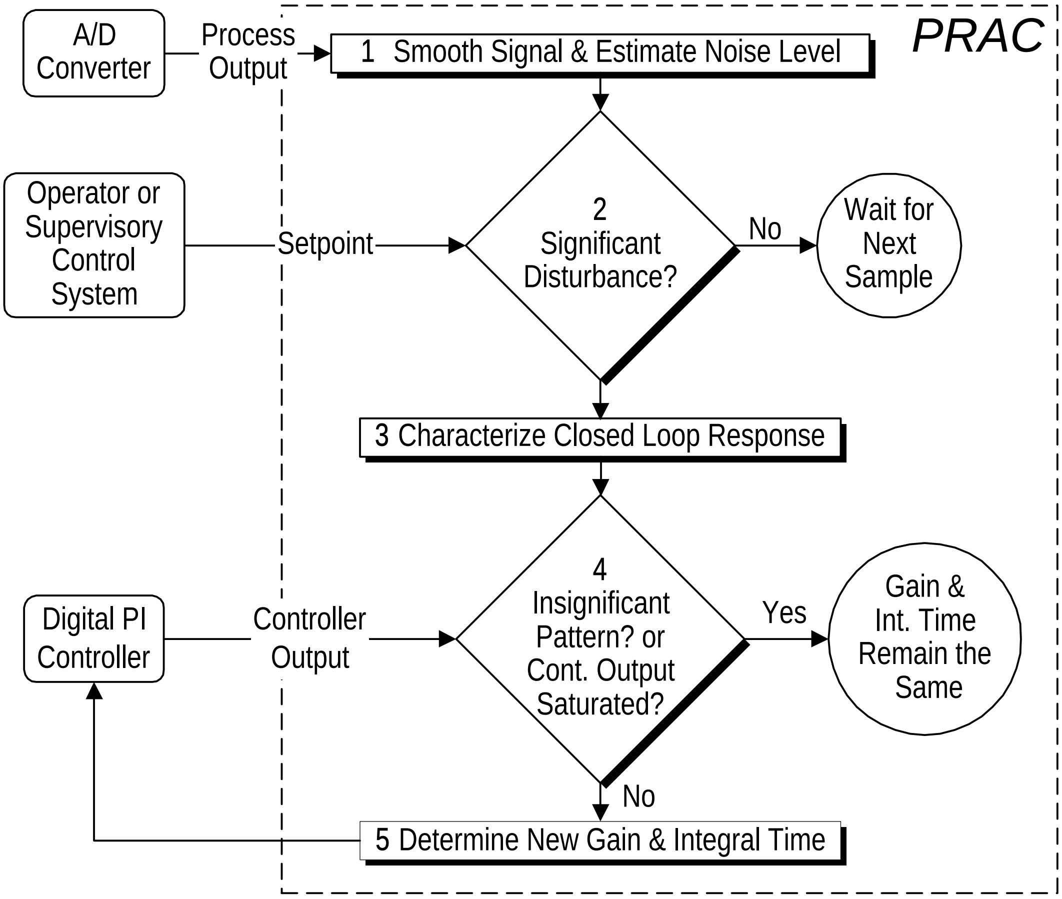

Figure 2 Flow chart showing the structure of the pattern recognition adaptive controller.

Block 3 characterizes the closed loop response by determining two dimensionless parameters. One of the parameters is a measure of the amount of oscillations, and the other parameter is a measure of the speed of response. The parameters are determined from the smoothed estimates from Block 1.

Block 4 stops the tuning process when the control loop when there is a system or component fault, such as a sensor fault. Also, this block stops the tuning process when the control loop is in a manual mode of operation load, or the load on the system exceeds the range of the process. The strategy of not updating the control parameters when the load exceeds the range of the process is analogous to anti-reset wind-up strategies for controllers with integral action.

Block 5 determines new values for the gain and integral time of the PI controller from the two dimensionless parameters from Block 3, an estimate of the signal size for the current disturbance relative to the noise estimate from Block 1, and an estimate of the signal size for the current disturbance relative to the signal size for past disturbances.

OVERVIEW OF DEVELOPMENT

When designing PRAC, our goal was to develop an easy to use adaptive controller that is robust and provides near-optimal performance in terms of the integrated absolute value of the error following both load disturbances and setpoint changes. We used the following four step procedure to develop PRAC.

Step 1 *Propose and Design Algorithm.*

This step involved proposing an algorithm and designing the algorithm. Simulations, linear least squares, and nonlinear optimizations were used to develop the equations and rules.

Step 2 *Simulation Tests.*
The performance of the proposed algorithm was compared with an optimal controller for 100,000 systems. The system with the worst performance was identified and the closed loop response for this system was studied. After determining a probable cause for the poor performance, we repeated step 1. After many iterations between steps 1 and 2, we proceeded to step 3.

Step 3 *Laboratory Tests.*
The algorithm was tested on the benchtop and in a HVAC laboratory. The benchtop tests involved controlling the voltage for an RC circuit. In the HVAC laboratory, tests were performed on a static pressure loop for an air handling unit that had a variable speed electric drive. After studying the benchtop test results, we revisited step 1 and made one revision to the algorithm.

Step 4 *Field Tests.*
Field tests were performed for a number of HVAC systems in different buildings around the United States. PRAC was able to tune all the systems that did not have mechanical problems. However, after studying the data from one of the initial field tests, we revisited step 1 and made one revision to the algorithm.

HVAC LABORATORY TEST RESULTS

Figure 3 shows the hardware used to during the laboratory and field testing. A digital communication trunk connects the portable computer to the air-handling unit (AHU) controller. The communication trunk sends data for the sensed value of the process output from the AHU controller to the portable computer. Also, the communication trunk sends data for the controller output from the portable computer to the AHU controller.

Figure 4 is the block diagram for the multi-rate control system that was used during the laboratory and field tests. The following modules were running in the portable computer: PRAC, the digital PI control algorithm described by Clarke (1984), a sampler that had a software adjustable sampling period, and a digital filter for removing aliases prior to sampling with a period of T. (The analog filter remove aliases prior to sampling with the A-D converter.) The sample time T was selected based on the type of loop being controlled. The AHU controller was the interface between the portable computer and the process.

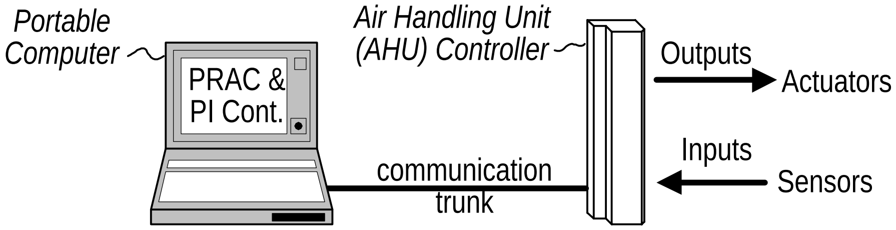

Figure 3 Hardware used during field and laboratory tests.

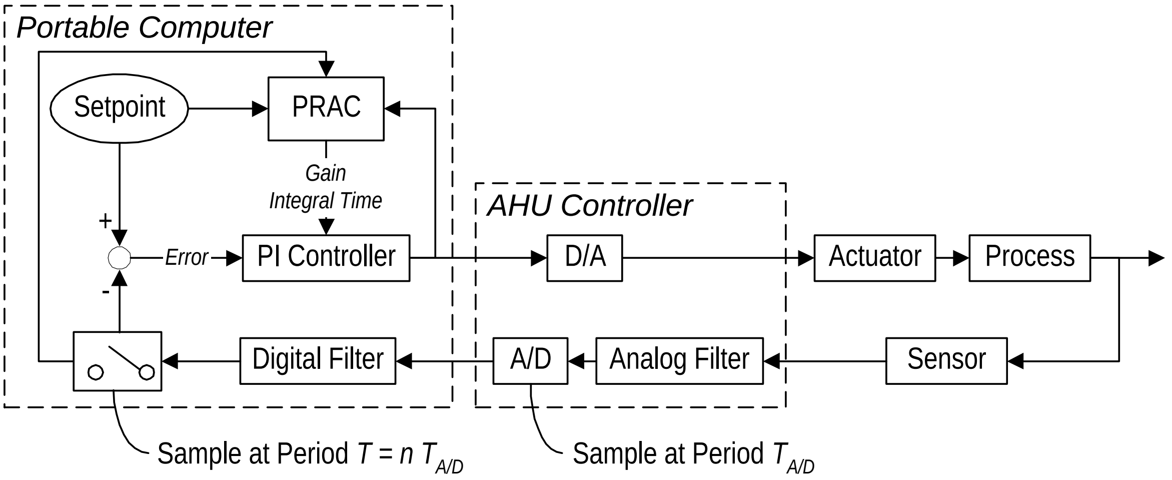

Figure 4 Block diagram of multi-rate digital control system used to test PRAC.

Figure 5 shows a schematic of a variable-air-volume air handling unit. The supply fan is controlled to maintain a static pressure in the supply duct at setpoint. ASHRAE (1995) recommends that the static pressure sensor be placed near the end of the supply air duct. Air handling units are usually controlled to maintain a constant discharge air temperature. This is accomplished by controlling a cooling coil, heating coil, or dampers to provide the desired discharge air temperature.

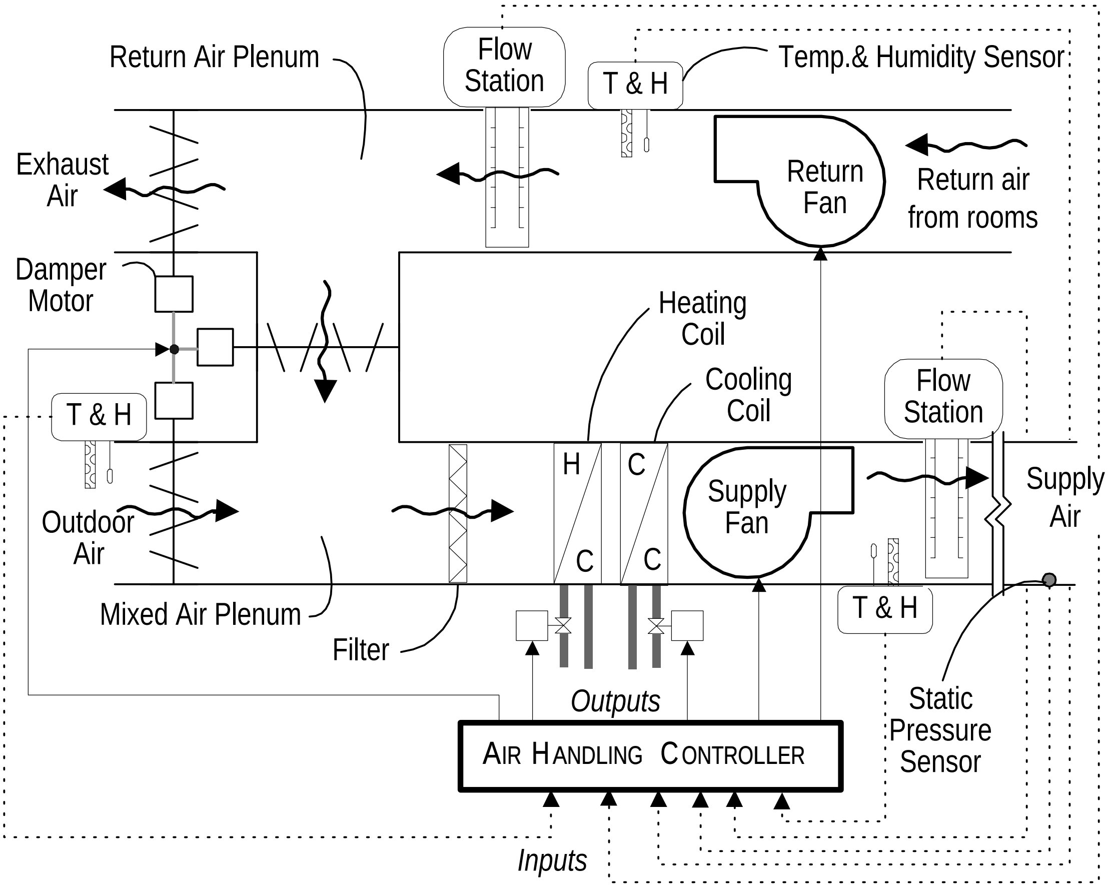

Figure 5 Schematic of variable-air-volume air-handling unit.

Laboratory tests were performed on the static pressure loop of a variable air volume (VAV) air handling unit located at the HVAC Laboratory of the Milwaukee School of Engineering. The static pressure sensor was placed at the end of the supply air duct. Eight pressure-independent variable-air-volume (VAV) boxes are attached to the supply air duct. The static pressure in the duct was controlled by changing the fan speed with a variable frequency drive. The design air flow rate was 3.54 m^3/s.

Figure 6 shows the steady state process curve for the static pressure loop. Data for the curve was obtained by sending a constant control signal to the variable speed drive and recording the static pressure after the system had stabilized. The control signal started at 0% command, and was increased in 10% increments up to a value of 100%. Then, the control signal was decreased in 10% increments back to a 0% command. The steady-state process curve is non-linear. Also, there is hysteresis non-linearity when the controller output goes from 60% to 100% and back to 60%.

The static pressure loop was tuned with four different initial conditions. Figure 7 shows the process output and setpoint when the initial conditions were sluggish. Figure 8 shows the controller output during the same time period as shown in Figure 7. At the beginning of the test, the controller was in a start-up mode. During the start-up mode, the controller output increases at a constant rate until the process output exceeds the setpoint. After the process output exceeds the setpoint, the controller switches from the start-up mode to PI control. During the initial time period of PI control, the controller output changes at a slow rate. After PRAC is turned on, the controller output changes at a faster rate. Notice that prior to the time PRAC is turned on, the process output is not approaching the setpoint. After PRAC is turned on, the process output approaches the setpoint. Also, the process output responds quickly to the setpoint changes. During the test, the controller gain increased from 0.0004 Pa^{-1} to 0.0014 Pa^{-1}, and the integral time decreased from 100 seconds to 7.8 seconds.

Figure 9 shows the process output and setpoint when the static pressure loop had aggressive initial conditions. Figure 10 shows the controller output during the same time period. Notice that after the transfer to PI control, the static pressure is oscillating from approximately 20 Pa to over 200 Pa. After PRAC is turned on, the oscillations begin to decrease. Eventually, the process output tracks the setpoint. During the test, the controller gain decreased from 0.04 Pa^{-1} to 0.0016 Pa^{-1} and the integral time increased from 3 seconds to 5.7 seconds.

Figure 11 shows the variations in gain and integral time for the four different initial conditions. Notice that the final values for the gain and integral time are in the same region. Figure 11 has labels for sluggish and aggressive initial conditions. Notice that the initial change in the controller parameters is larger for the aggressive initial condition. These large initial changes cause the control loop to quickly stabilize.

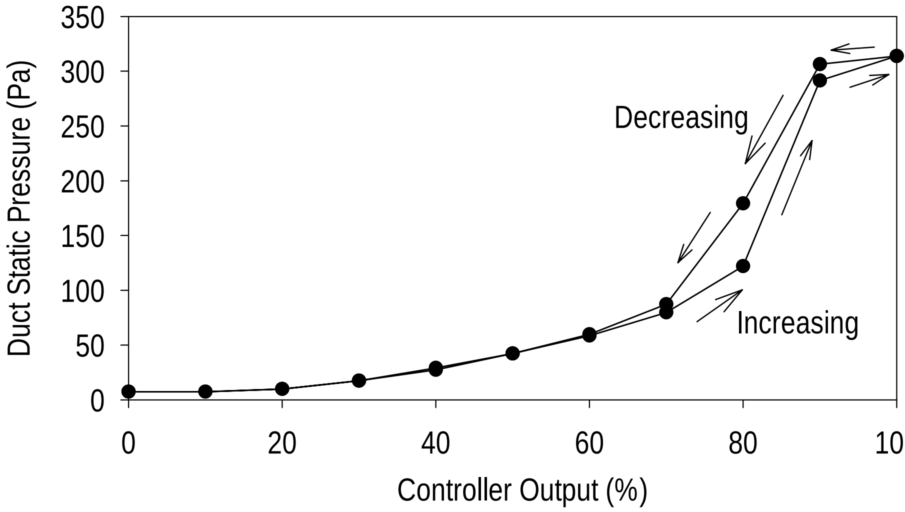

Figure 6 Steady-state characteristics of static pressure loop.

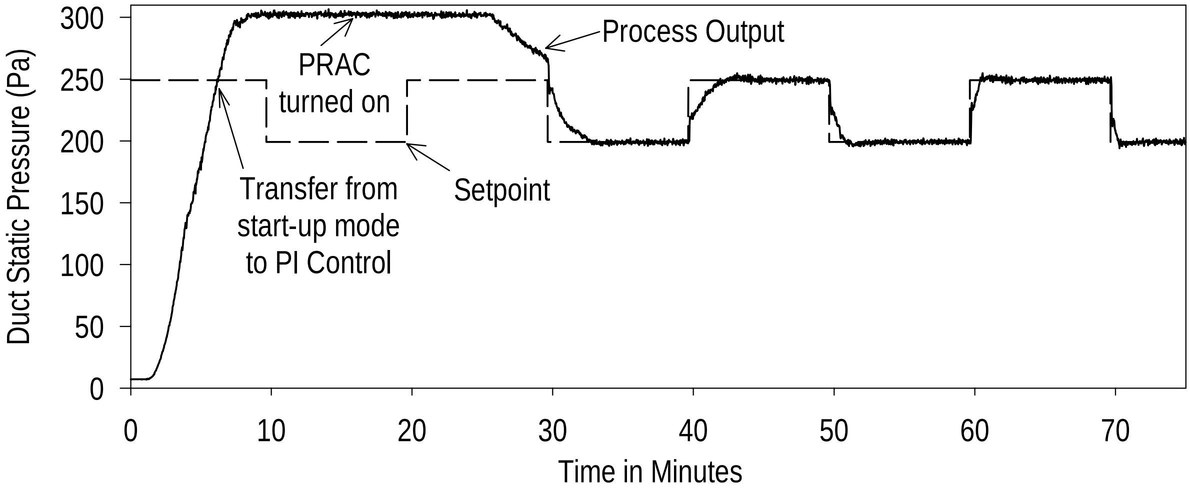

Figure 7 Tuning of laboratory static pressure loop with sluggish initial conditions.

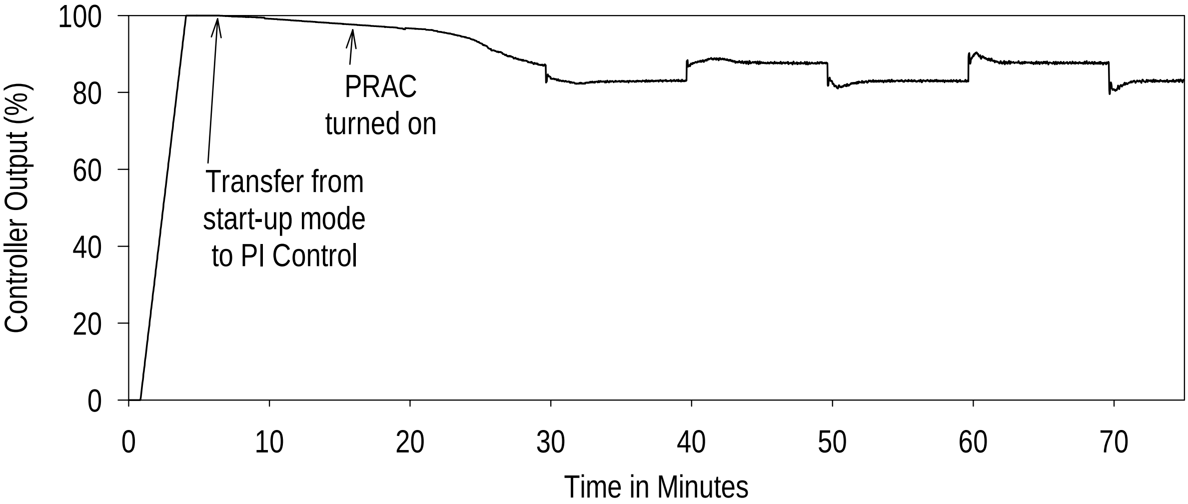

Figure 8 Controller output for laboratory test with sluggish initial conditions.

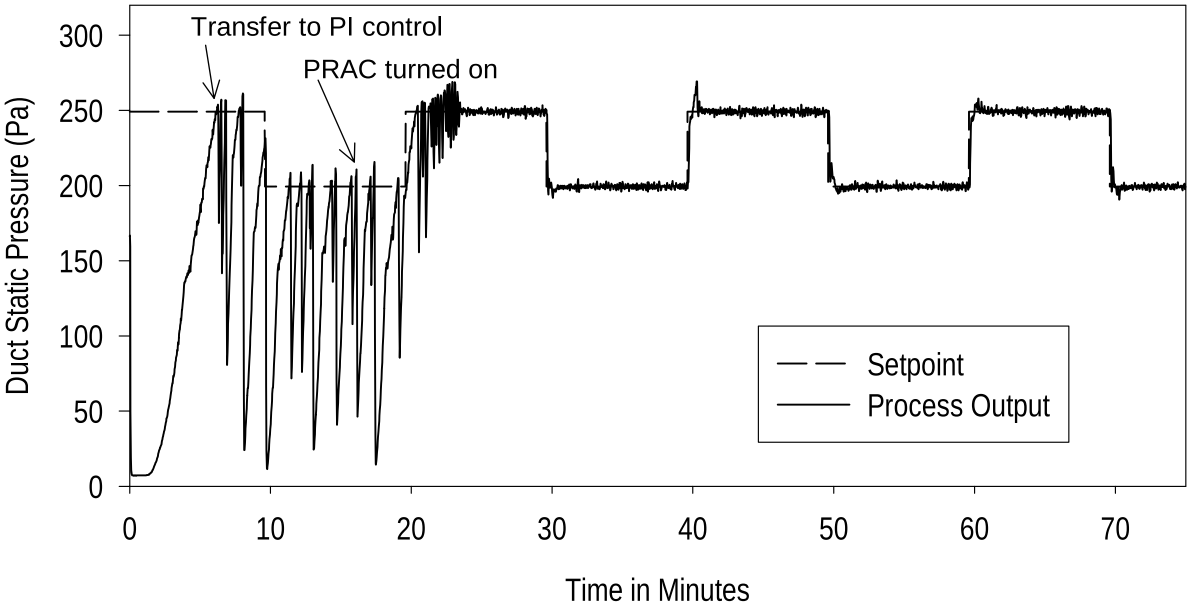

Figure 9 Tuning of laboratory static pressure loop with aggressive initial conditions.

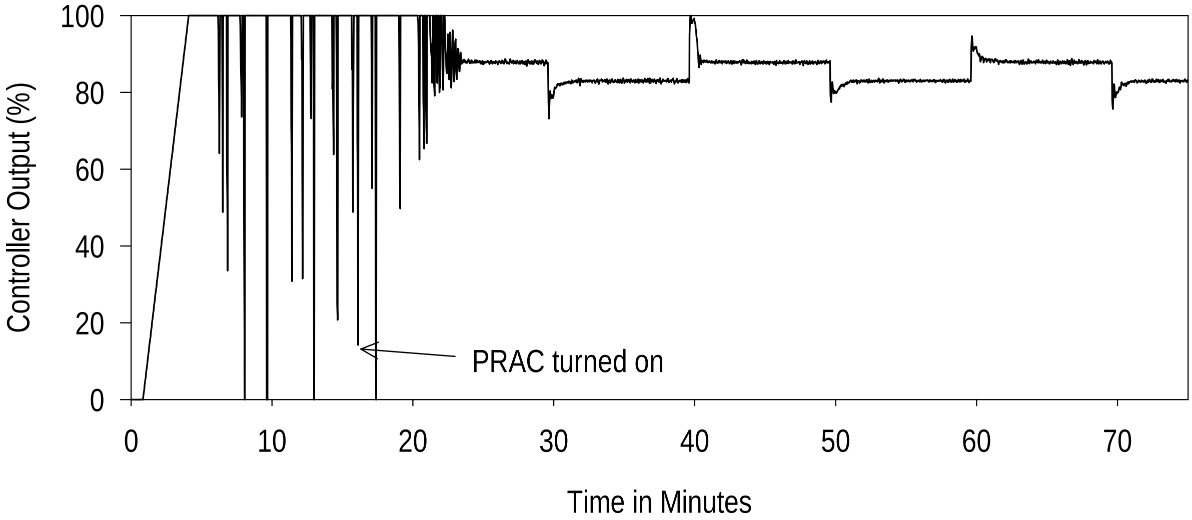

Figure 10 Controller output for laboratory test with aggressive initial conditions.

FIELD TEST RESULTS

We have tuned HVAC control systems in a number of buildings around the United States with PRAC. Specifically, we have tuned control systems in office buildings, high schools, community colleges, universities, national laboratories, department stores, hospitals, clinics, and large sports stadiums. To date, we have not had any problems tuning systems that did not have mechanical problems. Also, building service engineers have reported to us that PRAC has tuned a number of difficult control loops. This section presents field test results from five different sites we visited.

PRAC tuned the static pressure loop in a warehouse of a commercial airline. The controller issued a command to a variable speed drive that was connected to a fan. Figure 12 shows the process output and the setpoint. Prior to the time PRAC was turned on, the static pressure was oscillating around setpoint. After PRAC was turned on, the oscillations decreased. Notice that after PRAC was turned on, the static pressure followed the setpoint changes. Also, there appears to be a fair amount of noise in this process. Figure 13 shows the

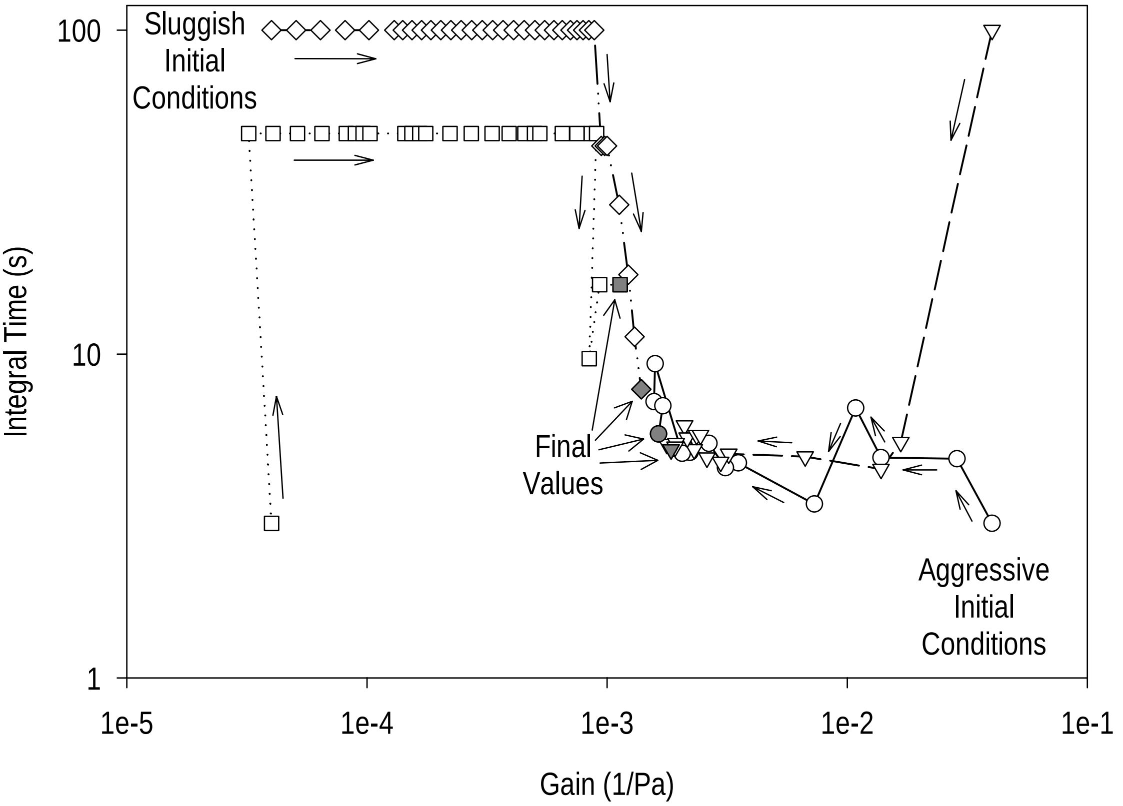

Figure 11 Variation of controller parameters for laboratory static pressure test.

controller output during the same time period as Figure 12. Notice that the controller output was oscillating between a 40% and 70%. After PRAC was turned on, the controller output stopped oscillating. The oscillations can cause the fan components to prematurely wear out. Also, the pressure-independent VAV boxes would have unnecessary wear because they would have to respond to the varying static pressure. Figure 14 shows the variation in gain and integral time during the static pressure test. For the first two updates, the gain and integral time make a large change. This causes the control loop to quickly stabilize. During the test, the gain decreased from 0.0010 Pa^{-1} to 0.0002 Pa^{-1}, and the integral time decreased from 30 seconds to 6.1 seconds.

PRAC tuned a static pressure control loop that used inlet vanes on the fan to adjust the static pressure. The AHU supplied air to eight graphics and photography classrooms at a technical college. There were 14 VAV boxes attached to the supply air duct, and the AHU could supply 4.72 m^3/s of air. Figure 15 shows the process output and setpoint. Notice that the initial response of the control system is very sluggish. After PRAC is turned on, the static pressure tracks the setpoint. Figure 16 shows the controller output for the same time period as shown in Figure 15. Figure 17 is a semi-log graph that shows the variation of gain and integral time during the test. (The x-axis for the gain is a log scale.) The gain increased from 0.00006 Pa^{-1} to 0.0036 Pa^{-1}, and the integral time decreased from 174 seconds to 9.3 seconds.

During certain time periods, the supply air temperature for an AHU can be maintained at setpoint by mixing return air from the zones with outdoor air. The supply air temperature is controlled by adjusting the position of the exhaust air damper, recirculation air damper, and outdoor air damper. PRAC tuned the damper control loop for a variable-air-volume AHU in a Technical College. The AHU could delivery 16.3 m^3/s of air to eight classrooms. Figure 18 shows the damper output and setpoint during the damper test. Notice that prior to the time

PRAC is turned on, the supply air temperature was oscillating around setpoint. After PRAC was turned on, the oscillations stopped. Also, the supply air temperature followed the setpoint. Figure 19 shows the controller output during the same time period as shown in Figure 18. Notice that prior to the time PRAC is turned on, the controller output is oscillating. These oscillation will cause the actuators and dampers to prematurely wear out. Figure 20 shows the variation in gain and integral time during the damper control test. During the test, the gain increased from -0.061 $°C^{-1}$ to -0.1 $°C^{-1}$, and the integral time increased from 30 seconds to 240 seconds.

At times, chilled water is used to cool the supply air. Figure 21 shows the process output and setpoint from a test on a chilled water coil at a technical college. The AHU could deliver 11.8 m^3/s of conditioned air to two kitchens and two classrooms. Notice that prior to the time PRAC was turned on, the supply air temperature was oscillating around the setpoint. After PRAC was turned on, the supply air temperature followed the setpoint. At approximately 1.5 hours, a load disturbance caused the supply air temperature to deviate from the setpoint. Then, the control system brought the supply air temperature back to the setpoint. Also, the control system responded well to the setpoint change at the end of the test. Figure 22 shows the controller output for the same time period as shown in Figure 21. Prior to the time PRAC was turned on, the controller output was oscillating. This oscillation in controller output may cause the damper and valve to prematurely wear out. Figure 23 shows how the gain and integral time varied during the test. The gain increased from -0.060 $°C^{-1}$ to -0.0039 $°C^{-1}$, and the integral time decreased from 120 seconds to 106 seconds.

When the outdoor air temperature is low, hot water or steam is used to raise the supply air temperature. Figure 24 shows the supply air temperature and setpoint from a test on a hot water heating coil at a corporate office building of a retailer. Notice that prior to the time PRAC was turned on, the process output was oscillating around the setpoint. After approximately one hour with PRAC on, the oscillations stopped and the supply air temperature approached setpoint. Also, the supply air temperature tracked both setpoint changes. Figure 25 shows the controller output during the test. The oscillations at the beginning of the test can cause the hot water valve and actuator to prematurely wear out. Figure 26 shows the variation of controller parameters. During the test, the controller gain decreased from 0.22 $°C^{-1}$ to 0.05 $°C^{-1}$, and the integral time increased from 60 seconds to 410 seconds.

CONCLUSIONS

This paper presented laboratory and field test results for a new pattern recognition adaptive controller (PRAC) that tunes proportional-integral controllers while under closed loop control. PRAC is easy to use, has low computational and memory requirements, and provides near-optimal performance. PRAC has successfully tuned HVAC control systems in a number of buildings.

The laboratory tests demonstrated that PRAC can tune systems that are either exhibiting sluggish or oscillatory behavior. The field test results are from various air handling units for five different control loops: static pressure control with a variable speed drive, static pressure control with inlet vanes, supply air temperature control with dampers, supply air temperature with a chilled water heat exchanger, and supply air temperature control with a hot water heat exchanger. PRAC successfully tuned all five control loops.

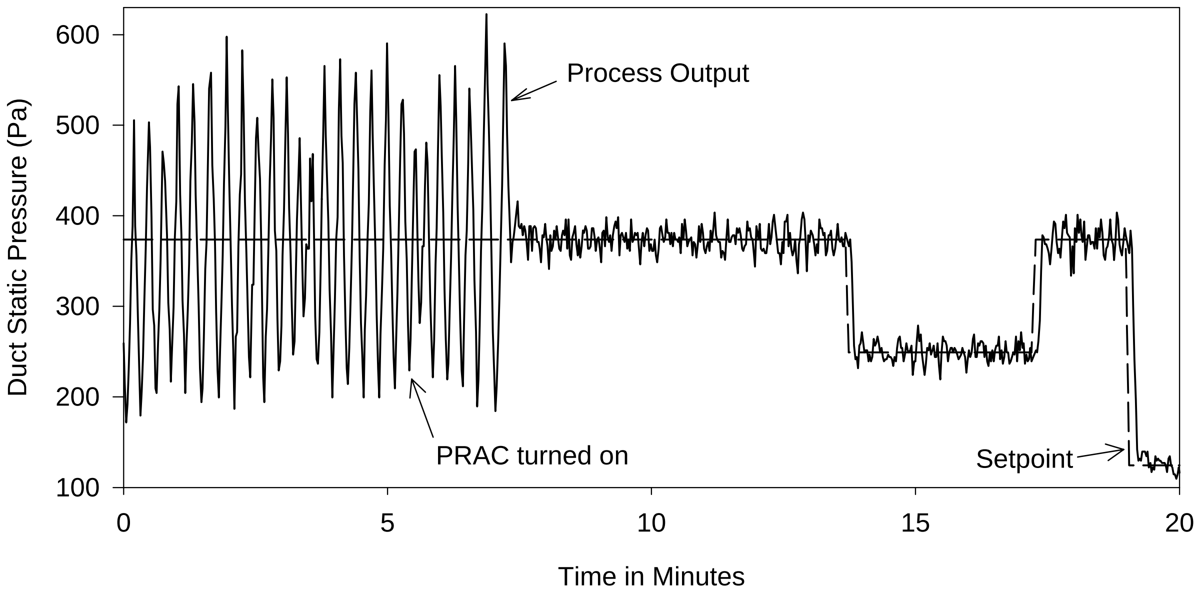

Figure 12 Process output and setpoint during static pressure test with variable speed drive.

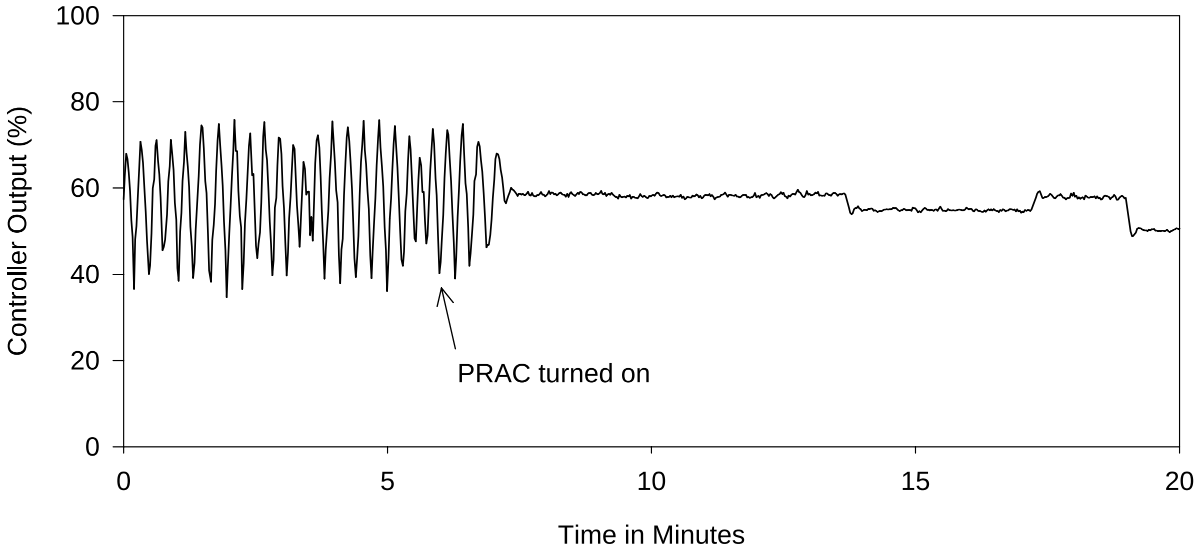

Figure 13 Controller output during static pressure test with variable speed drive.

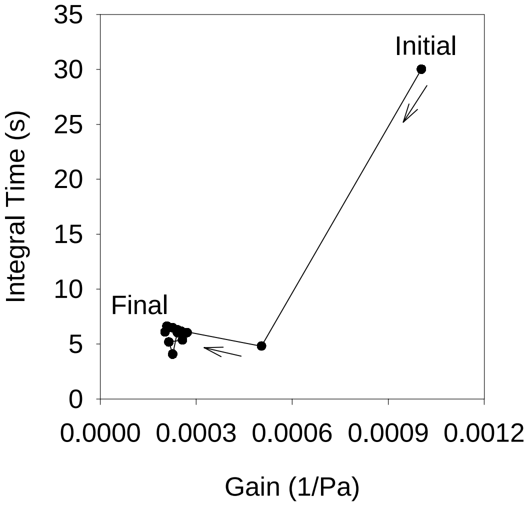

Figure 14 Gain and integral time during static pressure test with variable speed drive.

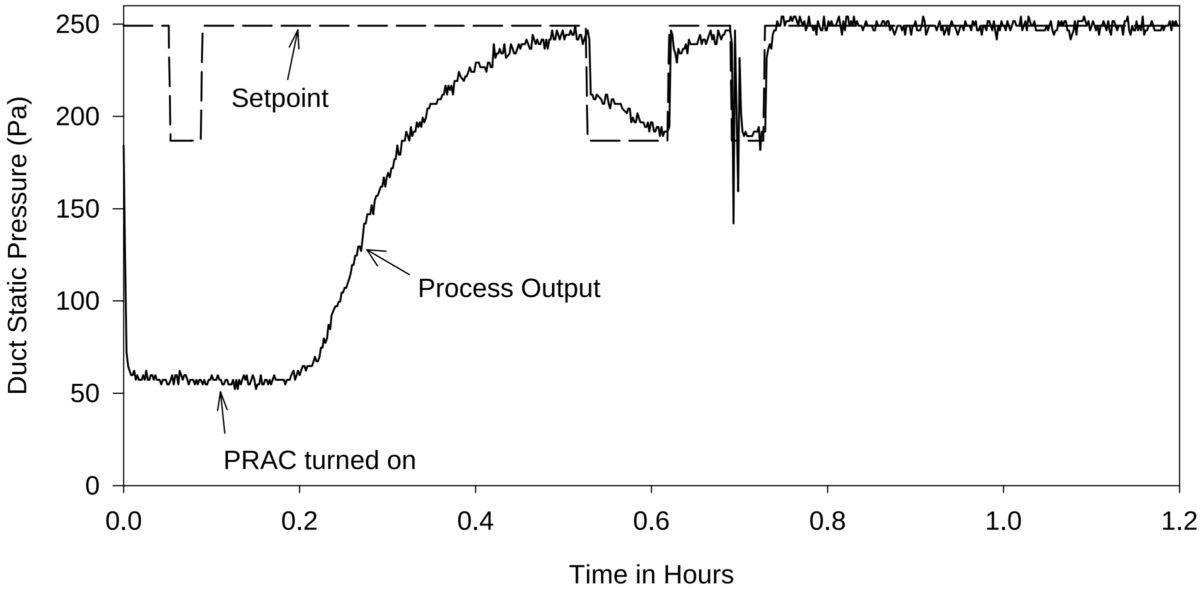

Figure 15 Process output and setpoint during static pressure test with inlet vane control.

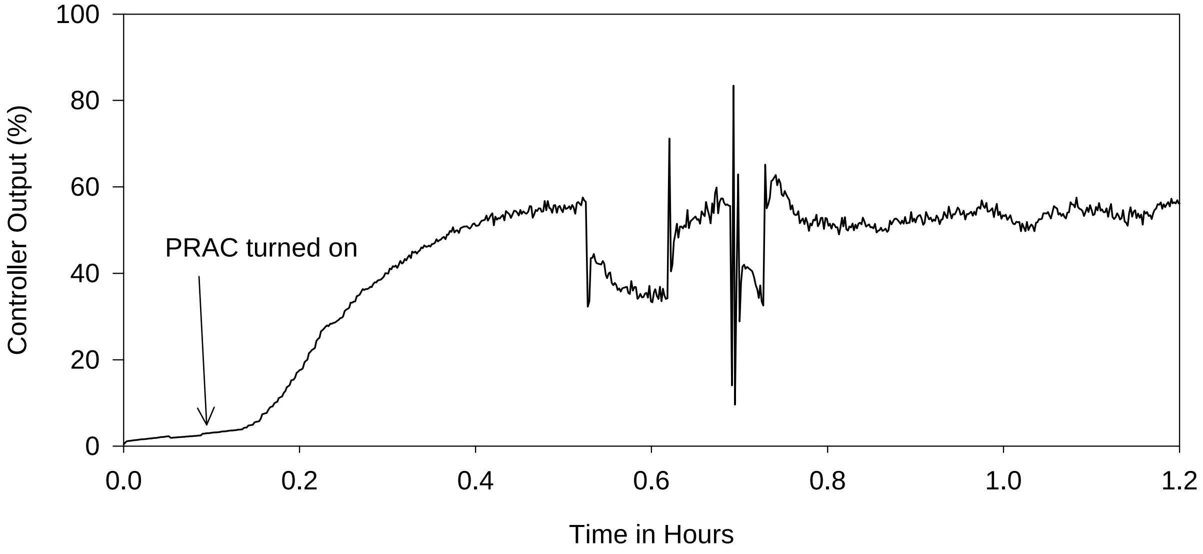

Figure 16 Controller during static pressure test with inlet vane control.

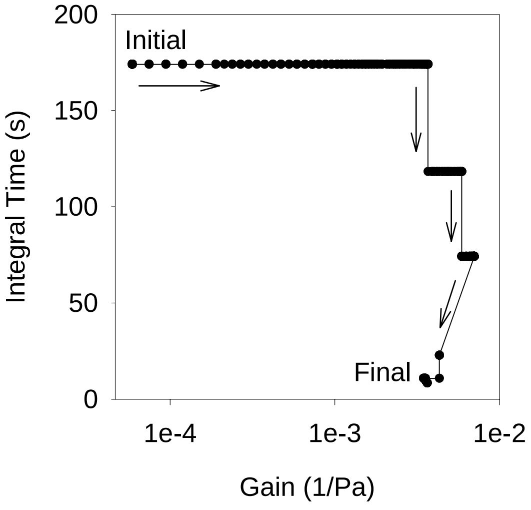

Figure 17 Gain and integral time during static pressure test with inlet vane control.

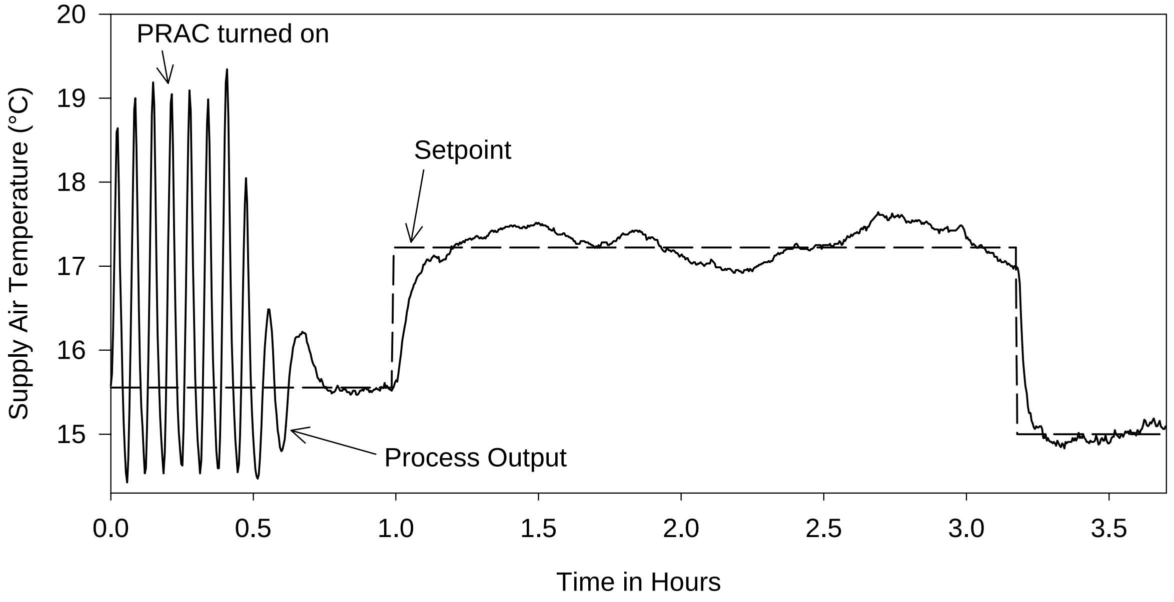

Figure 18 Process output and setpoint during damper control test.

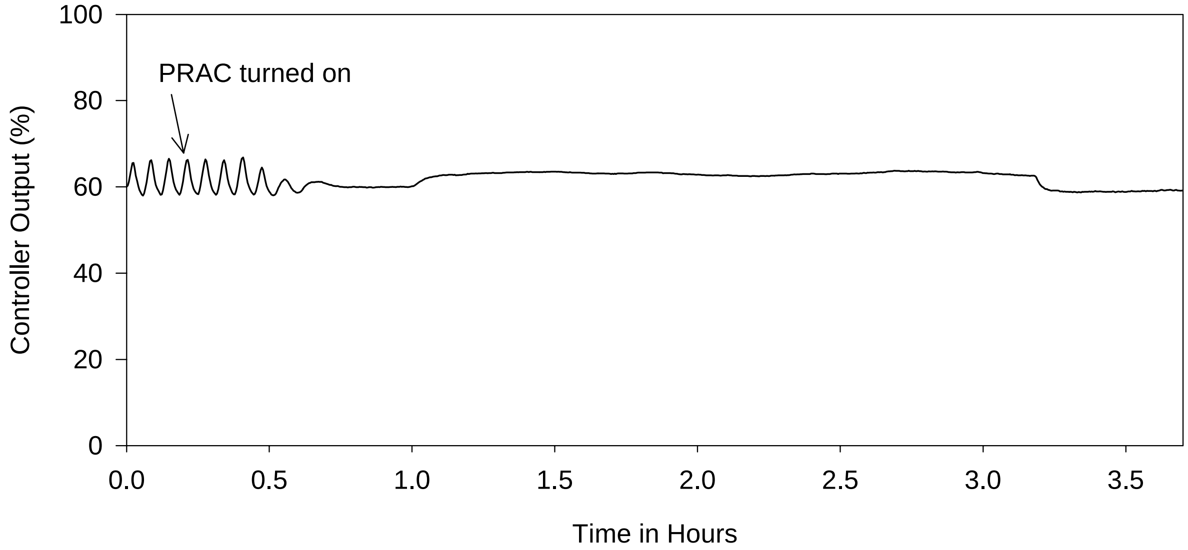

Figure 19 Controller output during damper control test.

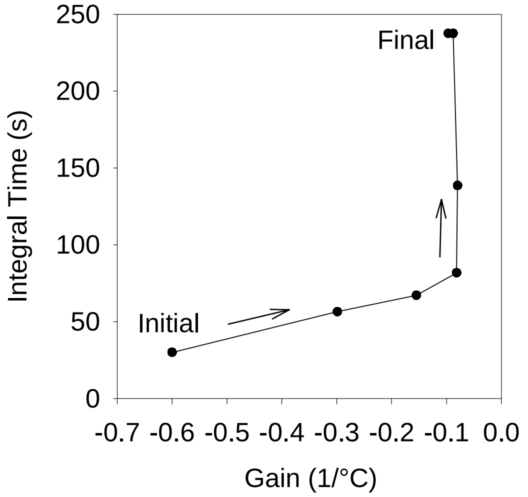

Figure 20 Variation of gain and integral time during damper control test.

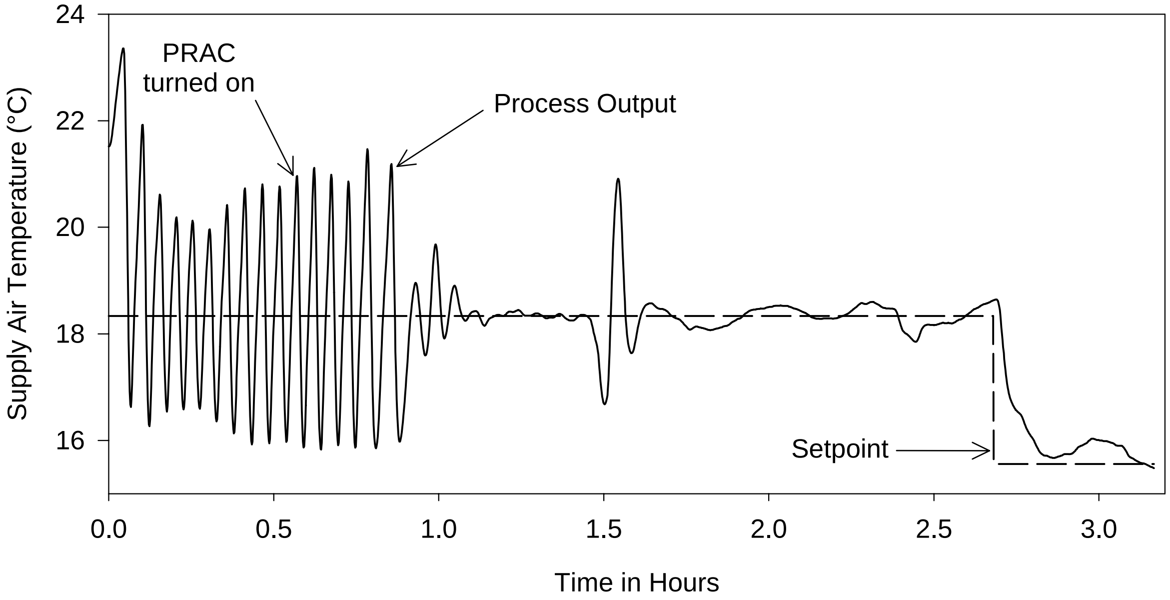

Figure 21 Process output and setpoint during cooling coil test.

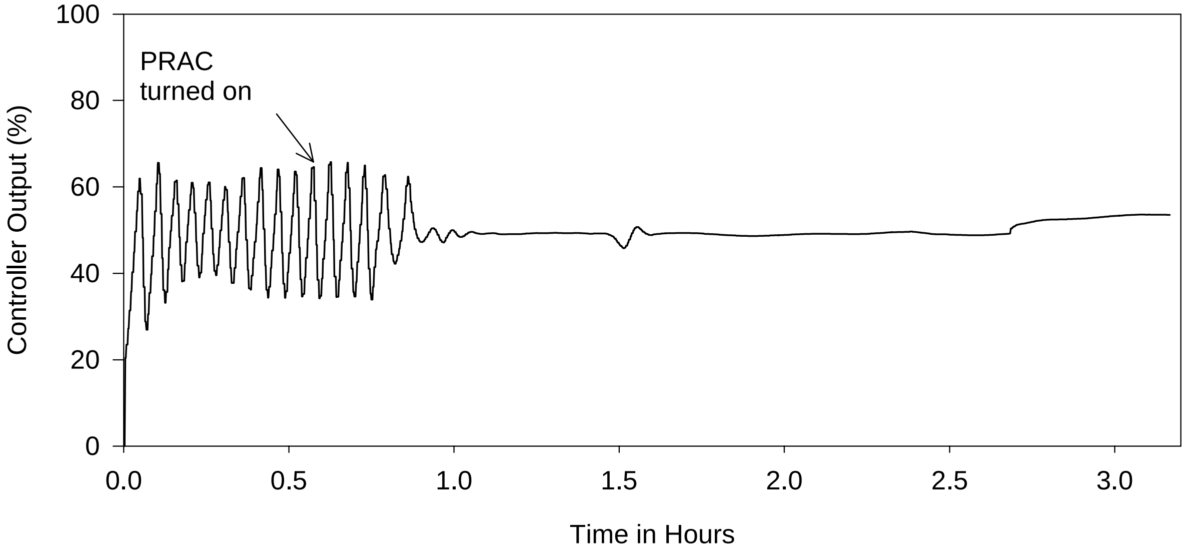

Figure 22 Controller output during cooling coil test.

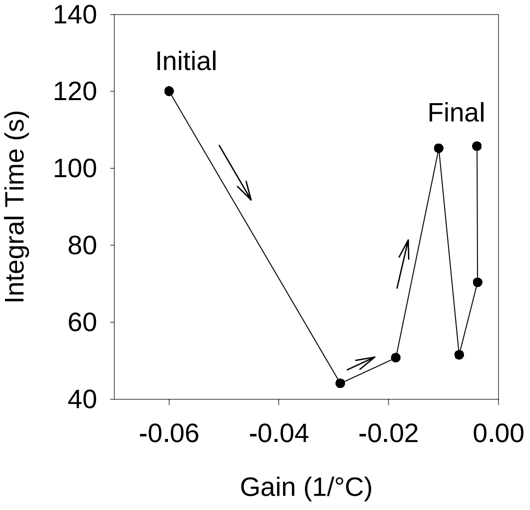

Figure 23 Variation of gain and integral time during cooling coil test.

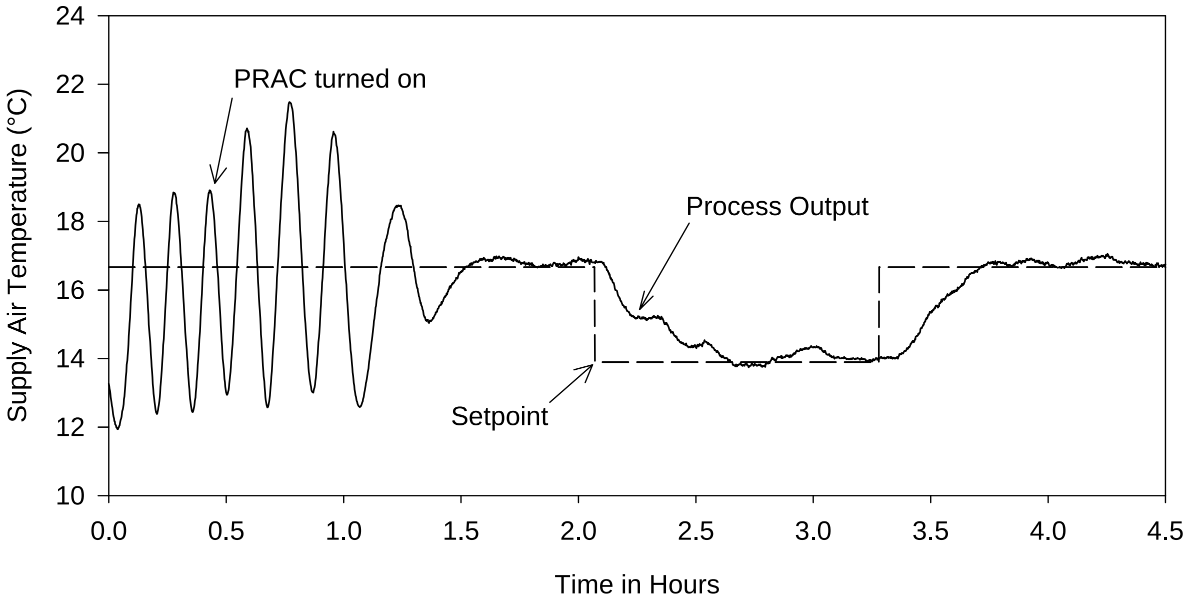

Figure 24 Process output and setpoint during heating coil test.

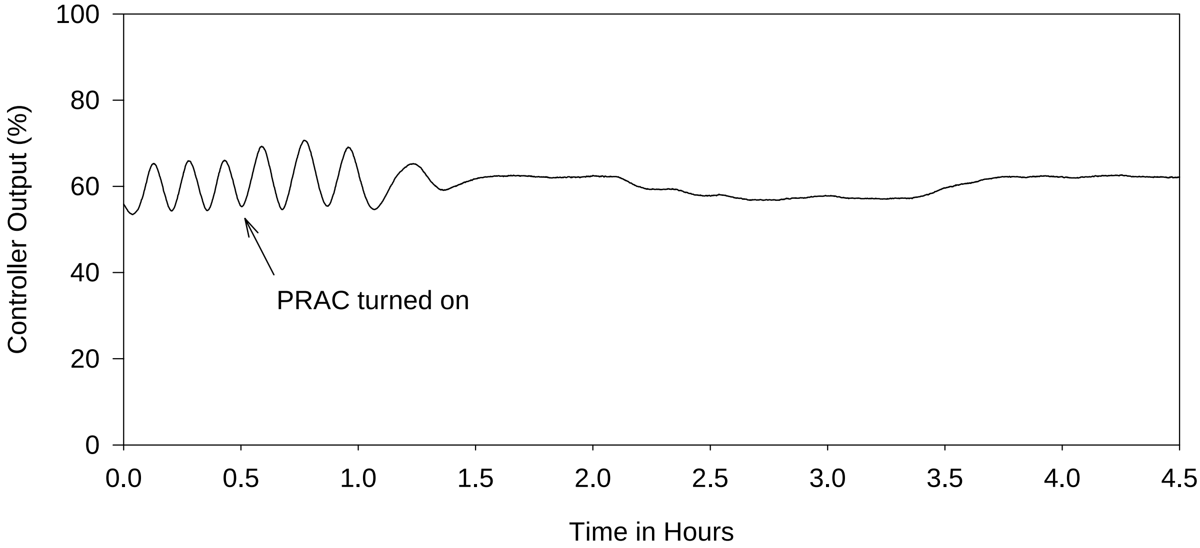

Figure 25 Controller output during heating coil test.

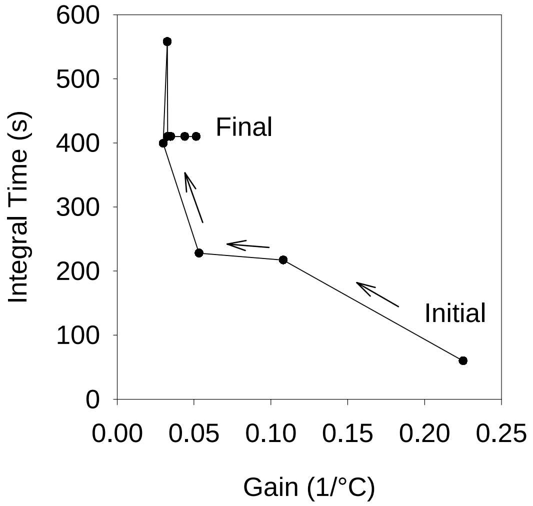

Figure 26 Variation of gain and integral time during heating coil test.

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