VisSim Tutorial Series

Heating, Ventilation, and Air Conditioning (HVAC) Controls: Variable Air Volume (VAV) Systems

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- *Biomedical Systems: Modeling and Simulation of Lung Mechanics and Ventilator Controls Design*. Mike Borrello, Metran America, Inc.
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- *Simulation of Communication Systems*. Eugene Estinto, Eritek, Inc.
- *Simulation of Motion Control Systems*. William Erickson, Indramat-Rexroth.

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Introduction

The purpose of Heating, Ventilating and Air Conditioning (HVAC) control systems is to keep people comfortable within an enclosed space. Although comfort control is thought of as achieving a desired temperature in a building, it is also achieved by maintaining a desired level of humidity, pressure, radiant energy, air motion and air quality.

One of the most popular HVAC applications, the Variable Air Volume (VAV) application, is designed to deliver low energy cost, low maintenance and good comfort performance. The VAV application controls the temperature inside a space by modulating the amount of air supplied to it. VAV systems, which are studied in this chapter, are easy to install, commission and service. They are also simple to understand and represent a good introduction to HVAC controls.

In this tutorial, the VAV system is analyzed, modeled and simulated. The air handling system, which provides air to the VAV system, is also studied and analyzed. When modeling the different components of the VAV system, practical models are used to capture the different characteristics of the system. The VAV system components used in this tutorial are fairly simplified using first order system modeling and piece-wise linear modeling techniques. The different models used to simulate the VAV system response are easy to develop and are great for engineers who are interested in observing the general behavior of the system rather than the minute details.

All of the models used in this tutorial are derived using English IP (Inch Pound) units instead of metric SI (Systéme International) units. Table 1 shows the IP unit abbreviations used in this tutorial.

Table 1. IP Unit Abbreviations

Abbreviation	**Definition**
Btu	British Thermal Units
Cfm	Cubic Feet per Minute
°F	Degrees Fahrenheit
ft	Feet
in	Inches
lb	Pounds
sqft	Square Feet

The VAV Air Handling System

The air handling system is the primary HVAC system in most building HVAC installations. This system, which is hidden from most building occupants, is the main system that delivers conditioned air to the entire building. The main responsibility of the air handling system is to supply the building with fresh and conditioned air, then exhaust it from contaminated and carbon dioxide (CO_2) air. Most air handling equipment is located on building rooftops. The size and configuration of the air handling unit, also referred to as the rooftop unit, depends on the size and requirements of the building HVAC specifications.

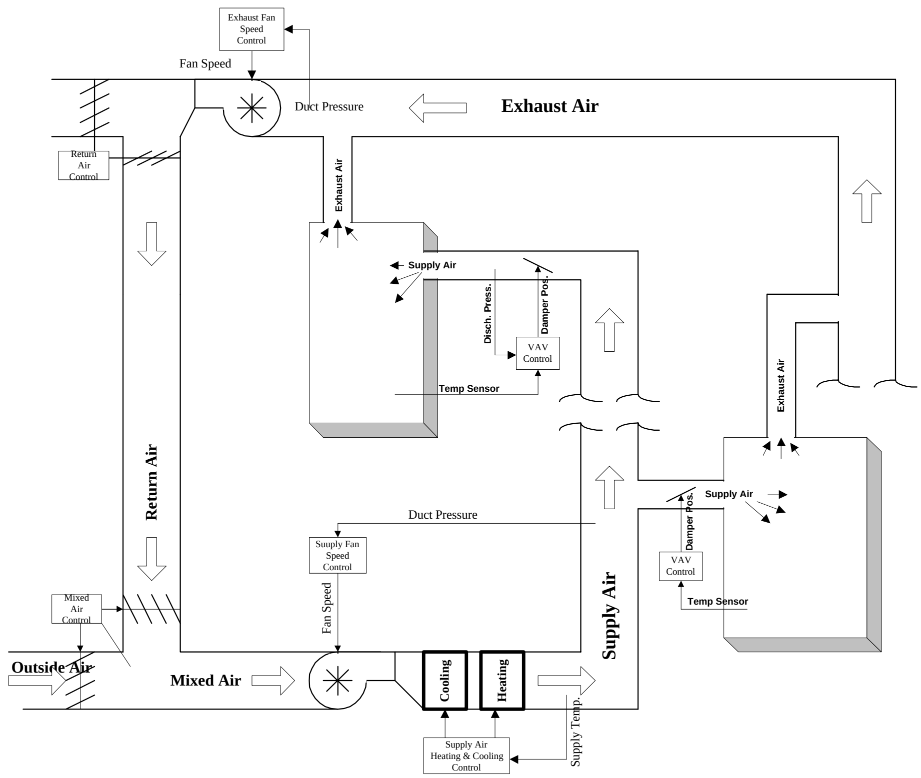

Figure 1. Air handling system

As shown in Figure 1, the air handling system delivers heated or cooled supply air to the multiple VAV systems attached to the building's air ducts. Since the VAV system control is dependent on the operation of the air handling system, it would be easier to understand the sequence of operation of the air handling system before analyzing and modeling the VAV control system.

The air handling unit consists of two main components:

- The air handling equipment, which consists of outside air dampers, mixed air dampers, heating coils, cooling coils, and supply air fans.
- The air handling controls, which consists of the electronic control hardware that sequences the operation of the air handling system.

The air handling control operation, as shown in Figure 1, is described by the following four steps:

1. Mix outdoor air with return air
2. Control the supply air pressure
3. Heat/cool the mixed air
4. Control the exhaust air pressure

The VAV System

The VAV control concept was derived from the realization that most of the air conditioning operation in a building is cooling only. Independently of the outdoor air climate conditions, most occupied rooms need cooling only to eliminate the energy loads caused by solar radiation, human occupancy, equipment and utility operation.

The operation of the VAV cooling-only control system, assuming that there is enough air pressure in the duct system and that the temperature of the supply air is cold enough, is described by the following steps:

1. The VAV controller monitors the temperature in the room.
2. If the room is warm, the VAV controller opens the supply air damper to allow more cold air into the room.
3. If the room is cold, the VAV controller closes the supply air damper, thus allowing the interior loads to heat up the room space.
4. If the room is occupied, the VAV supply air damper cannot be fully shut. The VAV controller has to maintain a minimum amount of fresh air, specified by the building designers, so that people occupying the room do not suffocate.

This cooling-only VAV control application, more specifically defined as the "single-duct, pressure-dependent, cooling-only" VAV application and shown in Figure 2, will be the main focus of the rest of this tutorial.

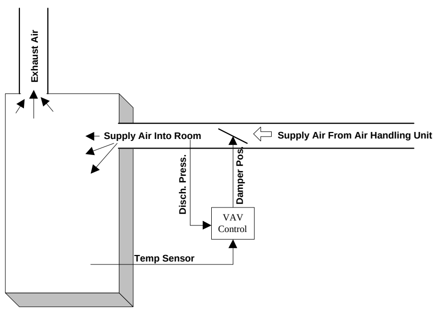

Figure 2. Single-duct, pressure-dependent, cooling-only VAV system

Like all control systems, this VAV system has three main components:

- The VAV process
- The VAV control
- Sensors and feedback components

Figure 3 describes the different control, process and feedback components of the VAV system.

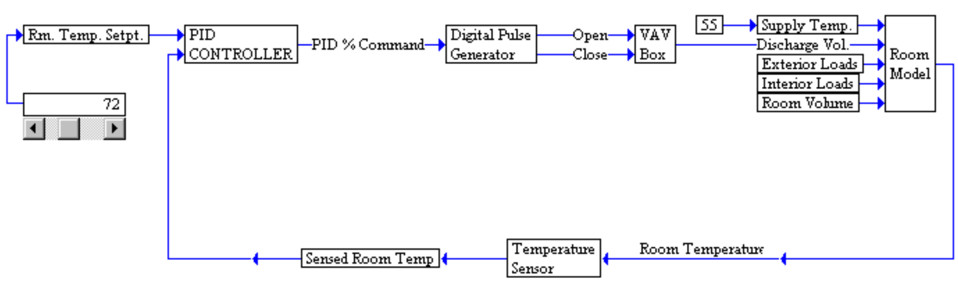

Figure 3. VAV system components

The VAV Process

The VAV process contains the following components:

- The room
- The VAV damper

The Room

Let's consider the case when the room is warm. As the temperature of the room increases, the VAV controller opens the damper to allow in more cold air. The heat generated by the internal and external loads are dissipated by mixing the room's warm air volume with the cold supply air volume.

The process of mixing and exchanging energy between air volumes is governed by the laws of thermodynamics. These laws describe the different behaviors of energy in gases, liquids and solids.

The first law of thermodynamics, referred to as the law of conservation of energy, states that the sum of all energies entering and leaving an enclosed space is equal to the rate of change of stored energy in the same space.

The equation describing the first law of thermodynamics is

$$Qin - Qout = \frac{d(Q)}{dt} \qquad (1)$$

where

Qin is the energy entering the room space

Qout is the energy leaving the space

d(Q)/dt is the rate of change of the stored energy

The energy Q of a gas is defined by the following equation:

$$Q = M \times Cp \times (\Delta t) \qquad (2)$$

where

M *is the mass of the gas.* M *of the gas is also defined as* $(V_{gas} \times \rho_{gas})$

Cp *is the specific heat constant*

Δt *is the room temperature differential. It is also equal to* $\frac{d(T_{gas})}{dt}$

Combining equations 1 and 2 and applying the resulting equation on the process of mixing the room's air volume with the supply air volume, the following equation 3, is obtained:

$$(Q_{interior} + Q_{exterior} + Q_{supply}) - Qout = (V_{room}\rho_{air}) \times Cp \times \frac{d(T_{room})}{dt} \qquad (3)$$

where

ρ_{air} *, Rho air, is the density constant of air*

V_{room} *is the volume of the room*

T_{room} *is the temperature of the room*

$Q_{interior}$ *is the energy generated by interior loads, such as people, lights, and computers*

$Q_{exterior}$ *is the energy generated by exterior loads, such as the sun and cold weather*

Since

$$Qout = M \times Cp \times (T_{room} - T_{air\ leaving\ room})$$

and

$$T_{room} = T_{air\ leaving\ room}$$

then

$$Qout = 0$$

Therefore

$$Q_{supply} = M \times Cp \times (T_{supply} - T_{room}),$$

$$Q_{supply} = K \times Volume_{SupplyAirFlow} \times (T_{supply} - T_{room}) \quad (4)$$

where

$Volume_{SupplyAirFlow}$ *is the volume of the air flow supplied into the room*

K *is a constant*

T_{supply} *is the temperature of supplied air into the room*

Combining equations 3 and 4 yields

$$Q_{interior} + Q_{exterior} + K \times Volume_{SupplyAirFlow}(T_{supply} - T_{room}) = V_{room} \times \rho_{air} \times Cp \times \frac{d(T_{room})}{dt} \quad (5)$$

To establish an equation that determines the room temperature, rewrite equation 5 as follows:

$$T_{room} = \frac{1}{V_{room} \times \rho_{air} \times Cp} \int \left[Q_{iinterior} + Q_{exterior} + K \times Volume_{SupplyAirFlow}(T_{supply} - T_{room}) \right] dt \quad (6)$$

Replacing the following constants with their value (in IP units), the following final equation is obtained:

$$T_{room} = \frac{1}{V_{room} \times 0.075 \times 0.241} \int \left[Q_{interior} + Q_{exterior} + 1.08 \times Volume_{SupplyAirFlow}(T_{supply} - T_{room}) \right] dt \quad (7)$$

where

Cp = *0.241 Btu/(lb °F)*

ρ_{air} = *0.075 lb/ft*^{3}

K = *1.08 (Cfm Btu)/(Hour °F)*

The VisSim simulation model of the room is described in Figure 4.

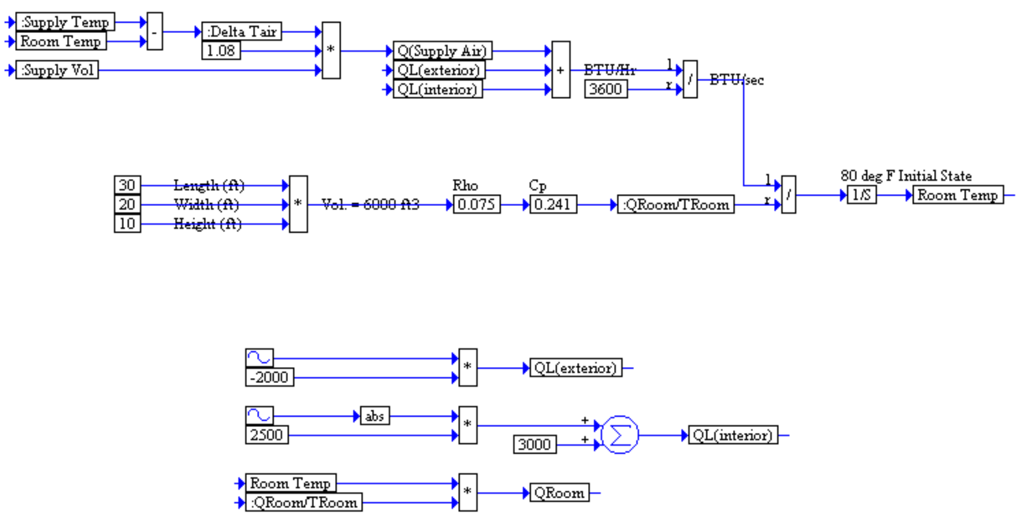

Figure 4. VisSim implementation of the room model

The VAV Damper

The VAV damper is a mechanical device that controls the amount of supply air flow discharged into the room. Although there are many damper designs available in today's HVAC industry, the most common damper design in VAV applications is a single-axle, circular, thin metal damper rotated by an actuator, as shown in Figure 5.

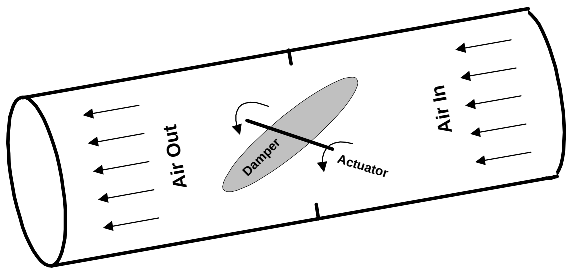

Figure 5. The VAV damper

The amount of air supplied by the damper into the room depends on the angle at which the damper is positioned. As can be seen in Figure 5, when the damper is at 90°, or 0% open, the damper is fully shut and no air is supplied to the room. On the other hand, when the damper is at 0°, or 100% open, the damper supplies the maximum amount of air allowed by the duct pressure. Therefore, by observing the amount of flow supplied by the damper versus the damper position, the damper characteristics can easily be seen as illustrated in Figure 6.

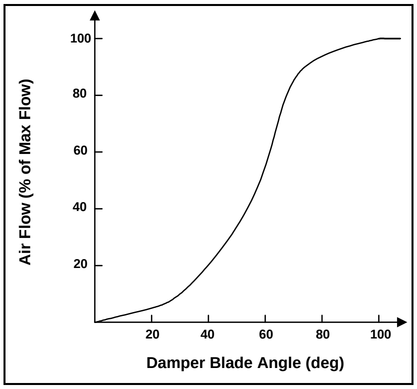

Figure 6. Damper characteristics

From Figure 6, it is concluded that there is a nonlinear relationship between the amount of air supplied and the damper's position. In fact, laboratory experiments have shown that for most commercial VAV dampers, when the damper position is approximately between 0% to 15%, the amount of air supplied by the damper is pretty low. The same experiments reveal that when the damper position crosses the 15% to 70% range, the air flow suddenly becomes more significant and small position changes cause high air flow gains. Finally, when the damper position is approximately between 70% to 100%, low air flow gains are observed. This is because most of the air flow has been already delivered by the time the damper position reaches the 60% to 70% range, and additional angular increments of the damper cause low air flow gains.

The nonlinear characteristics of the VAV damper are usually modeled with a third or higher order polynomial. These models can get a lot more complicated depending on the type of damper and the level of sophistication required from the model. However, since we are trying to capture the general dynamics of the damper characteristics, a simplified piece-wise linear model can be satisfactory.

To model the damper characteristics using a piece-wise linear model, the following algorithm is used:

Begin Algorithm A-1

If (Damper Position <= 18%) Then

    a = 0.5, b = 0

Else If (Damper Position >= 18%) AND (Damper Position <= 68%) Then

    a = 1.66, b = -20.88

Else If (Damper Position >= 68%) Then

    a = 0.25, b = 75.0

Supply Air Flow = (a * (Damper Position) + b) * (Maximum Air Flow /100)

End Algorithm A-1

Figure 7 shows the VisSim implementation of the piece-wise linear model described by algorithm A-1.

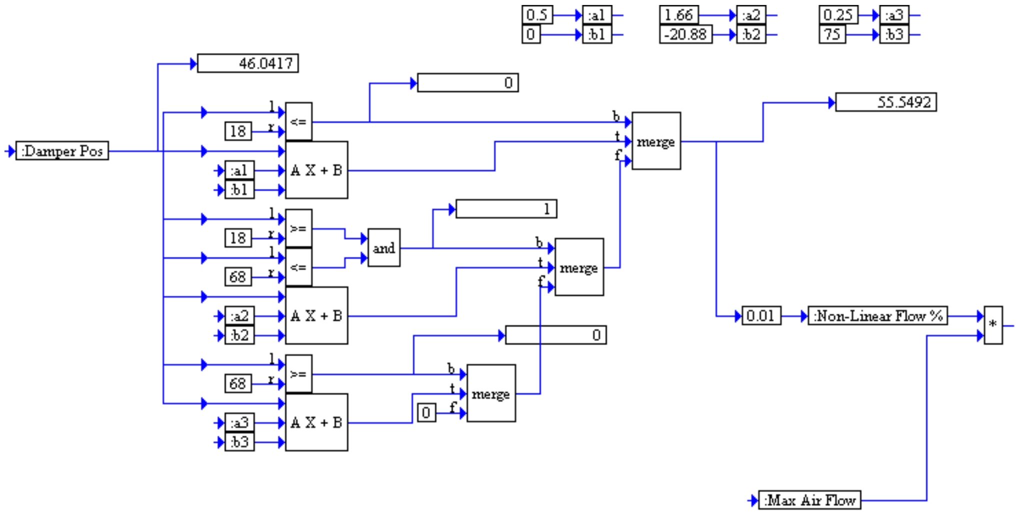

Figure 7. Piece-wise linear damper model described by algorithm A-1

A VisSim plot of the response of the damper model is shown in Figure 8.

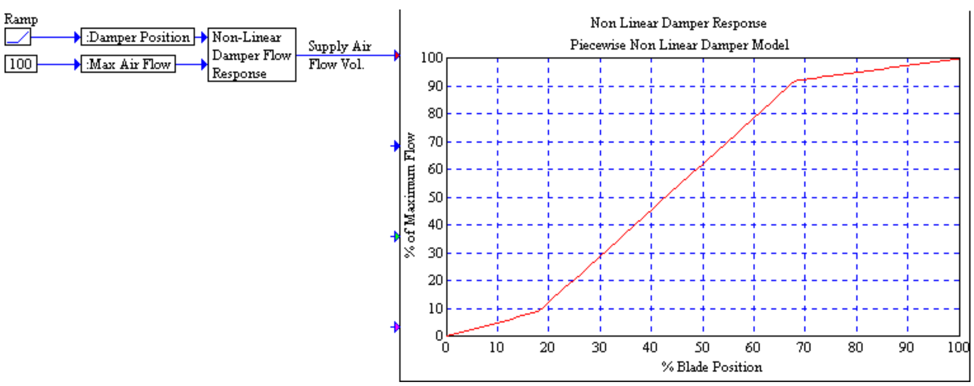

Figure 8. Piece-wise linear damper characteristics

Note the similarities between Figure 6 and Figure 8, and how the piece-wise linear model was able to approximate the characteristics of the damper response without using a complicated third or higher order polynomial model.

The damper can also be sized using the room equations developed earlier. Using equation 4, the maximum air flow volume which eliminates the different internal and external room loads, is described as follows:

$$Q_{supply} = K \times Volume_{SupplyAirFlow} \times (T_{supply} - T_{room})$$

$$Q_{supply} = K \times MaxVolume_{SupplyAirFlow} \times (T_{supply} - T_{room}) \qquad (4)$$

Therefore

$$MaxVolume_{SupplyAirFlow} = \frac{Q_{supply}}{K \times (T_{supply} - T_{room})} \quad (8)$$

where

$MaxVolume_{SupplyAirFlow}$ is the maximum air flow per minute delivered by the damper

Q_{supply} is the supply air load, also referred to as the sensible load of the room

T_{room} and T_{supply} are the temperatures of the room and the supply air, respectively

The VAV Control

Most VAV controllers are mounted on the VAV box hardware. The embedded VAV controller, which usually contains the control electronics and the actuator, mounts directly on the VAV damper actuator axle, as shown in Figure 9.

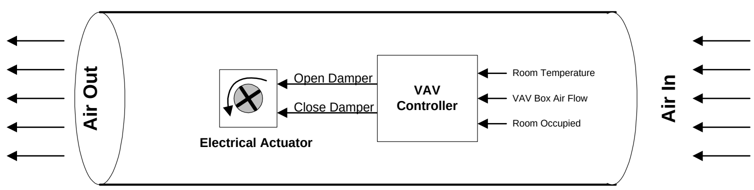

Figure 9. Installed VAV box with controller

The VAV controller that matches this application, single-duct, pressure-dependent, cooling-only VAV, is constructed from four main components:

- A PID controller
- A pulse width modulator
- An electric two-state damper actuator
- Sensors and feedback components

The PID Controller

The Proportional, Integral and Derivative (PID) controller is designed to monitor the room temperature and control the VAV damper position. The PID control algorithm used to develop the VAV system is a standard PID controller with anti-windup and lag filter derivative calculation, as shown in Figure 10.

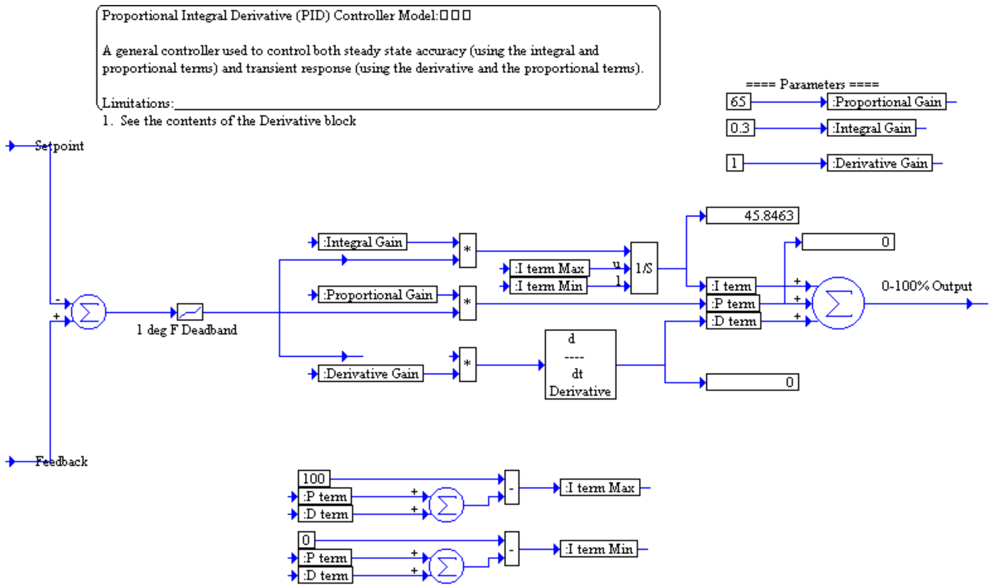

Figure 10. Implementation of the PID controller

This PID controller can be developed using the already existing PID controller found in VisSim's Control Toolbox.

The Pulse Width Modulator

The general definition of a pulse width modulator (PWM) is that it is a control component that transforms analog signals into digital pulses. In today's HVAC component market, it costs less to command the damper position through a pair of pulse width modulated output points than through a single analog output point. This is because digital point data acquisition costs less than analog point data acquisition. Therefore, it is more economical to output digital Open/Close signals to a two-state VAV actuator than to output analog 0% to 100% commands to an analog VAV actuator. In addition, because most VAV building installations contain hundreds of VAV boxes, building owners can save considerably on their VAV installations by choosing pulse width modulated output points instead of analog output points.

To transform the PID analog commands into digital pulses, a PWM is needed. The modulator estimates the position of the damper and sends a stream of Open/Close pulses until the commanded position is reached. If the estimated position is lower than the commanded position, the PWM sends a stream of Open pulses. Similarly, if the estimated position is greater than the commanded position the PWM sends a stream of Close pulses.

For example, if the VAV actuator stroke time is 1 minute (that is, the actuator goes from to 0% to 100% in 1 minute) and the PID commands a 50% position, given an initial damper position of 0%, the PWM does the following:

- Sends 30 consecutive 1 second Open command pulses, where each pulse causes the VAV damper actuator to open by 1.667%
- Estimates the damper position and when the estimated position is at 50% (within a deadband), it stops driving the actuator
- The final position of the damper = Initial position + 30 $\times$ 1.667 = 0% + 50% = 50%

If the initial position of the VAV damper is 75%, the PWM does the following:

- Sends 15 consecutive 1 second Close command pulses, where each pulse causes the VAV damper actuator to close by 1.667%
- Estimates the damper position and when the estimated position is at 50% (within a deadband), it stops driving the actuator
- The final position of the damper = Initial position - 15 $\times$ 1.667 = 75% - 25% = 50%

It is obvious that when using the two-state digital actuator, the accuracy of the damper position is sacrificed. The precision inconsistency is illustrated when the initial estimated position is not equal to the “real” position of the damper. To accomplish better damper position tracking accuracy, the following alternatives are available:

- Use an accurate analog actuator which commands the damper position directly from the PID output.
- Install a position feedback device such as a resistive feedback potentiometer. Note that installing extra devices on the VAV box can affect its manufacturing and installation costs.
- Use a PWM and apply overdrive when the estimated damper position reaches 0% or 100%.

To ensure that the position of the damper is synchronized with the pulse width modulated commands, an overdrive algorithm is added to the PWM’s logic. The overdrive algorithm, although very simple, is a very effective approach to solving the synchronization problem. The overdrive is applied every time the estimated damper position is either at 0% or 100%.

When the estimated damper position reaches 0%, the actual damper position might be at 0% or at a percentage that is near 0%, maybe 5% or 10%. This percentage uncertainty might cause unwanted damper leakage. In addition to damper leakage, as the position uncertainties accumulate during the day long VAV operation, the control system might lose track of the damper position and be way off the actual value. This causes bad control especially when these tracking errors reach magnitudes greater than 50%.

The overdrive algorithm is describe below.

Begin Algorithm A-2

If (The Estimated Damper position > The Upper overdrive threshold) Then

    For (time = 0 to time <= Stroke time)

        Command damper OPEN for Stroke Time

If (The Estimated Damper position < The Lower overdrive threshold) Then

    For (time = 0 to time <= Stroke time)

        Command damper CLOSED for Stroke Time

End Algorithm A-2

Figure 11 shows the VisSim implementation of the overdrive algorithm described by algorithm A-2.

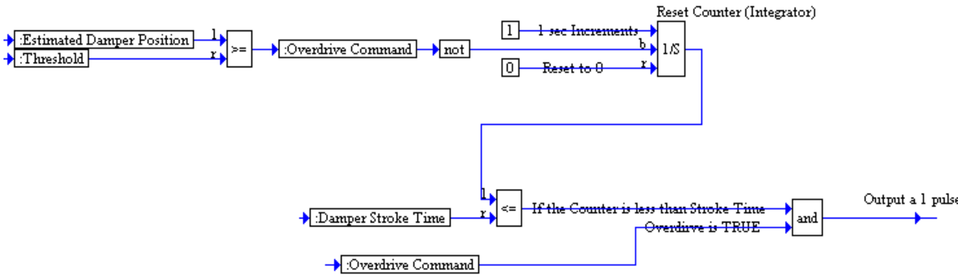

Figure 11. Overdrive algorithm implementation in VisSim

The VisSim implementation of the PWM with overdrive is shown in Figure 12.

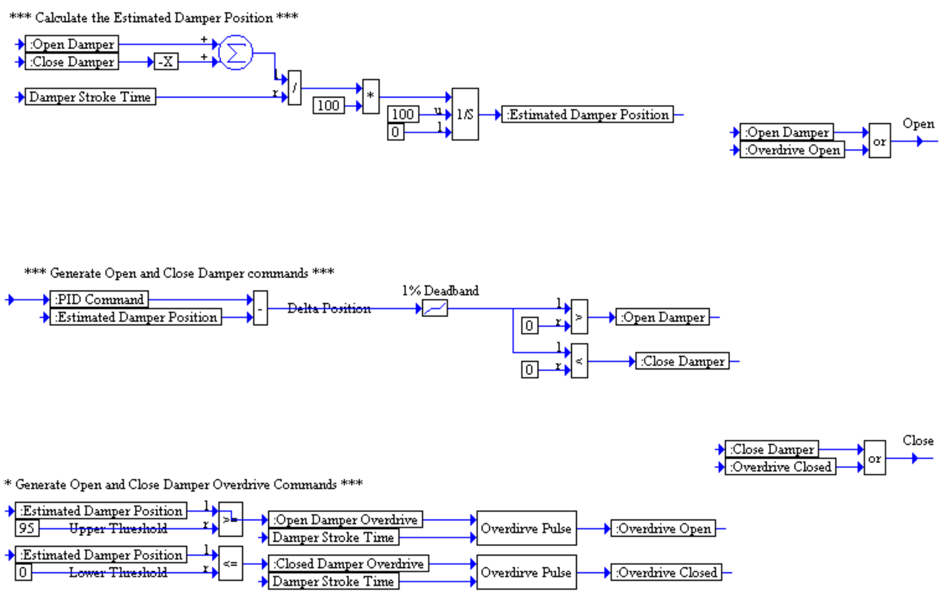

Figure 12. VisSim implementation of the PWM with overdrive

The Electric Two-State Damper Actuator

The damper actuator used in this VAV system is a two-state digital input (Open/Close) electric actuator. The actuator receives streams of Open or Close pulse width modulated signals, then rotates the damper axle based on the width and direction of the signals.

The two-state electric damper actuator model is implemented with an anti-windup integrator described by the following equation:

$$Present\ Position = Old\ Position + \frac{1}{StrokeTime} \times (Present\ Command\ Time\ duration) \times Direction \tag{9}$$

where

Direction = +1 if the command is Open

Direction = -1 if the command is Close

The anti-windup integrator algorithm, based on the previous equation is described by the following algorithm:

Begin Algorithm A-3

If (Present Position >= 100%) AND (OPEN COMMAND)

Present Position = 100%

If (Present Position <= 0%) AND (CLOSE COMMAND)

Present Position = 0%

Present Position = Old Position + (1/strokeTime) × (PresentCommandTimeDuration) × Direction.

End Algorithm A-3

Since VisSim already offers a built in anti-windup integrator block, called `limitedIntegrator`, the VisSim implementation of the actuator is very simple and is shown in Figure 13.

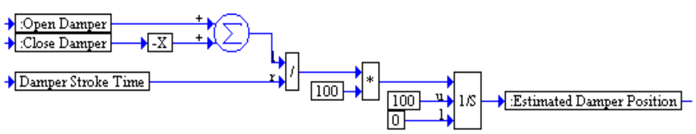

Figure 13. Electric two-digital input actuator

Sensors and Feedback Components

Only the room sensor is discussed in this section because it is the only sensing component in the VAV application.

The Room Sensor

The room sensor is typically a nickel- or platinum-resistive element and is highly sensitive to temperature changes. As the temperature of the room changes, the resistance of the metal fluctuates due to the temperature dependent dilatation properties of the metal.

The room temperature sensor senses the temperature of the room, using its resistive element, then generates a voltage which is linearized and fed back to the VAV controller. The voltage signal generated by the sensor is obtained by mounting a current source across the resistive element. The voltage magnitude, based on Ohm's Law, is equal to the product of the magnitudes of the current source and the sensing element's resistance.

The linearized resistance response to temperature versus time is approximated by a linear first order system with a Laplace transform of the following structure:

$$Room\ Temperature\ Sensed(S) = Actual\ Room\ Temperature(S)\ x \frac{K_p}{\tau . S + 1} \qquad (9)$$

where

K_p is the gain of the linearized sensor, for most linearized sensors $K_p = 1$.

τ (Tau) is the time constant of the sensor. When adding the dynamics of the plastic enclosure of the sensor, typical value of τ are about 1 to 5 minutes.

The VisSim representation of the first order approximation of the sensor is shown in Figure 14.

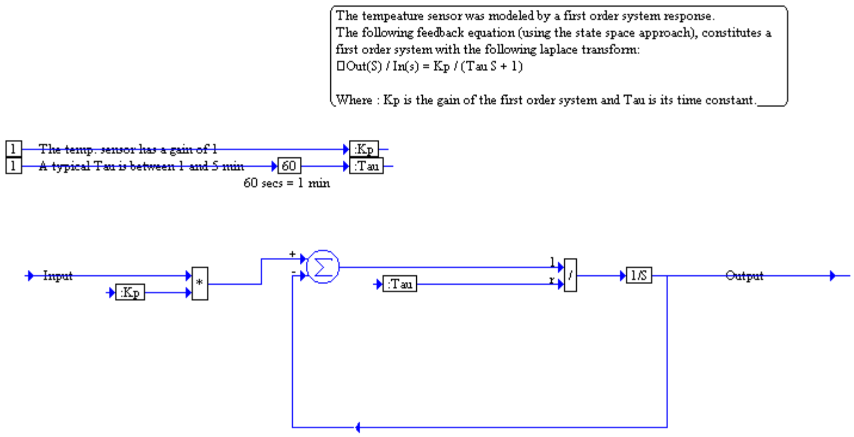

Figure 14. First order room temperature sensor

System Simulation and Observations

In this section, all the VAV models developed earlier are put together and simulated. Then, the results are observed and discussed.

To test the control algorithm and understand the dynamics of the VAV system, the room model is disturbed using disturbance loads that simulate daily environmental room conditions. As mentioned earlier in equation 6, the room model has three load components:

- Interior loads generated by constant and changing load disturbances
- Exterior loads generated by the outdoor climate
- Negative loads generated by the control system to maintain the temperature setpoint

As shown in Figure 15, an aggressive set of simulated loads is applied to the room model. The load profile applied in this simulation is constructed from the following load components:

- A constant internal load component of magnitude 3000 Btu/hr, is used to simulate constant loads inside the room, such as lights, computers, and coffee machines.
- A changing internal load component simulated by a full wave rectified sinusoidal signal with a magnitude of 2500 Btu/hr and a period of 1.75 hours. This load component simulates loads generated by groups of humans entering a conference room, generating heat, then leaving.
- A changing external load component simulated by a sinusoidal wave of magnitude 2000 Btu/hr and a period of 4.6 hours. This load component simulates the outside temperature drop during early morning and later afternoon, and outside temperature increase around 10 am to 2 pm.

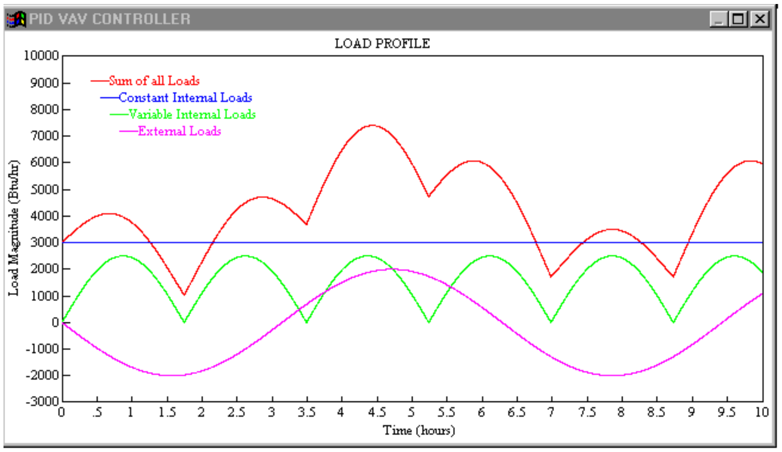

Figure 15. Load profile

As loads change in the room, the VAV control system generates "anti-loads" or "negative" loads to cancel the heat generated by the internal and external temperature disturbances . The VAV system controls the position of the damper and regulates the amount of cold supply air needed to eliminate all the loads in the room. To properly control the temperature of the room, the VAV system has to first reach the temperature setpoint, then match the disturbance loads. If the disturbance loads are matched and the temperature of the room is at setpoint, the temperature setpoint is maintained. Figure 16 shows how the VAV system is able to eliminate the internal and external disturbance loads by generating a negative load, from supply air, that matches the magnitude of the room loads.

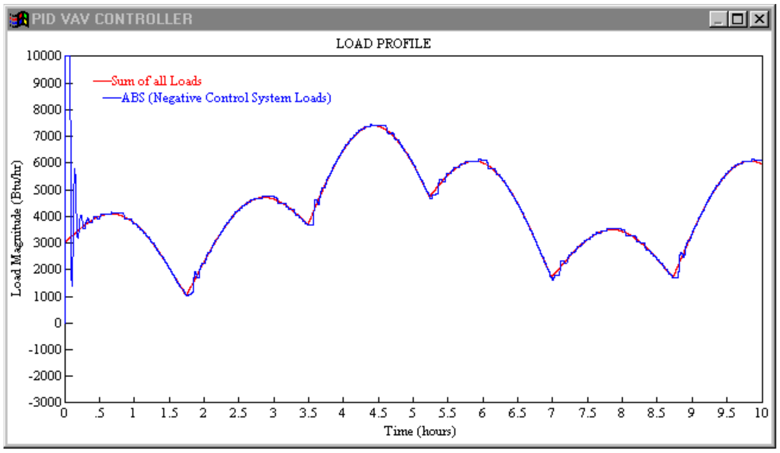

Figure 16. Load control

Once the temperature setpoint is reached and the loads are matched, the VAV controller easily maintains the setpoint because all loads are canceled and no temperature change is generated.

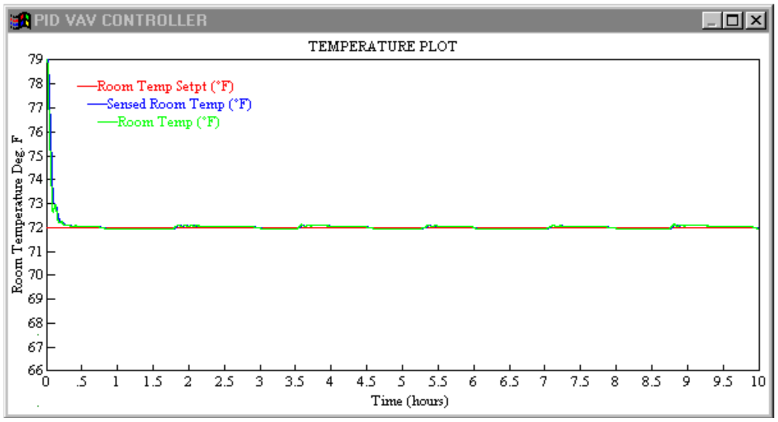

Figure 17. VAV system temperature control

Figure 17 shows the performance of the PID controller, which maintained a +/- 0.1 °F error during a 10 hour simulation, which corresponds to the building occupancy time. The PID tuning parameters were obtained using off-the-shelf tuning utilities.

Figure 18 shows the VAV damper position commanded by the PID controller during the simulation. Note that there is an obvious correlation between the damper position and the magnitude of the load disturbances, as shown by Figures 16 and 18. This direct correlation between the damper position and the system loads is easily deducted and explained. As the loads increase in the room, more cold air is required and the damper position is increased. Similarly, when the loads decrease, the VAV control throttles back the damper position to maintain the temperature setpoint of the room.

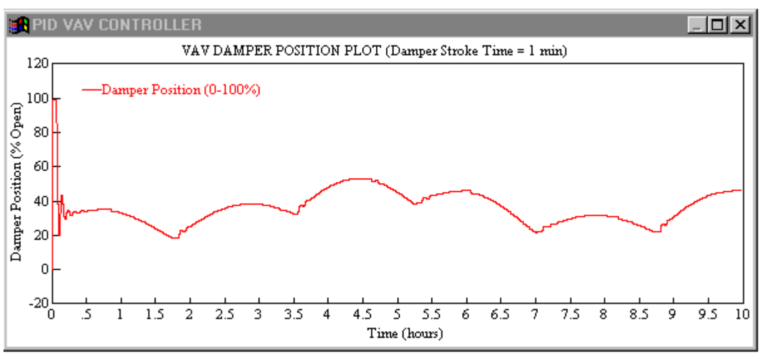

Figure 18. VAV damper control

To show the effect of the air handling pressure control on the VAV sequence, the maximum amount of air flow delivered by the VAV damper is reduced from 600 Cfm to 300 Cfm. This reduction in the amount of air delivered by the air handling system is encountered when the main supply air fan is not properly tuned or installed. The VAV damper response, shown in Figure 18, observed during the 3.5 to 6.5 hours interval of the simulation, describes the operation of a starved VAV damper. The VAV controller senses a load in the room and commands the damper to open and supply more cold supply air. However, since there is not enough cold air pressure to eliminate the disturbance loads, the VAV damper stays at 100% until the room loads decrease. The VAV damper is said to be "starved" because it is commanded at maximum without it being able to satisfy the room loads. VAV box starvation is common for over-sized and under-pressurized VAV installations, it is also more common in hot climates.

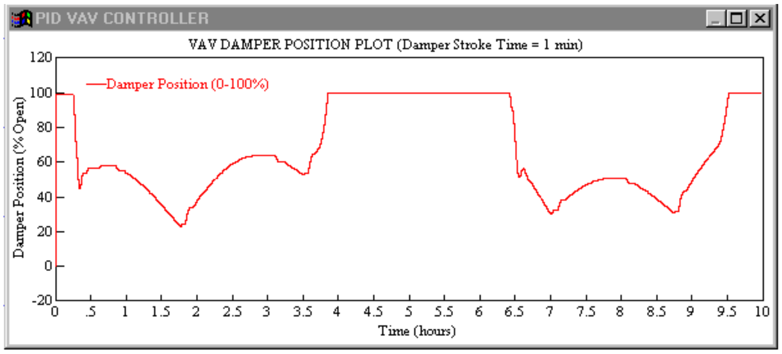

Figure 19. Starved VAV damper response

Figure 20 shows the load matching response of the starved VAV system. Note that when the loads are greater than the system's capacity, the VAV damper is at maximum, as shown in Figure 19, and the temperature is above the temperature setpoint, as shown in Figure 21.

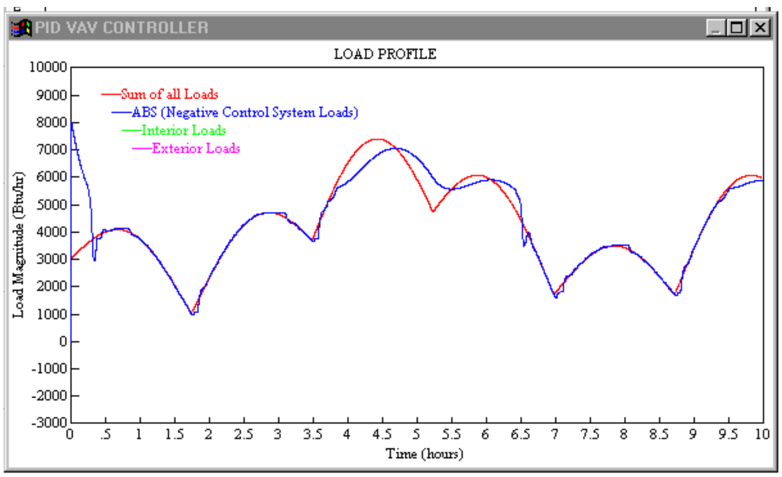

Figure 20. Starved VAV system load matching

From Figure 21, it is observed that the VAV system does not have enough capacity to maintain the temperature setpoint. In other words the system's capacity cannot eliminate the disturbance loads. As a result, the room temperature deviates from the required setpoint while the VAV damper is at its maximum position.

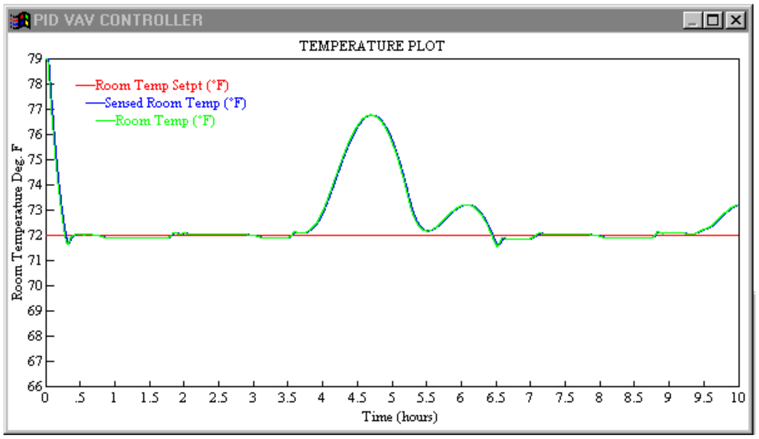

Figure 21. Starved VAV system temperature control

The same starved behavior is also observed when increasing the temperature of the supply air. In fact, if the temperature of the duct system supply air is increased, the VAV system is not able to generate enough "negative" loads to eliminate the disturbances in the room.

Figures 22, 23 and 24 show the response of the VAV damper, load matching and temperature control when the supply air temperature is increased from 55 °F to 60 °F.

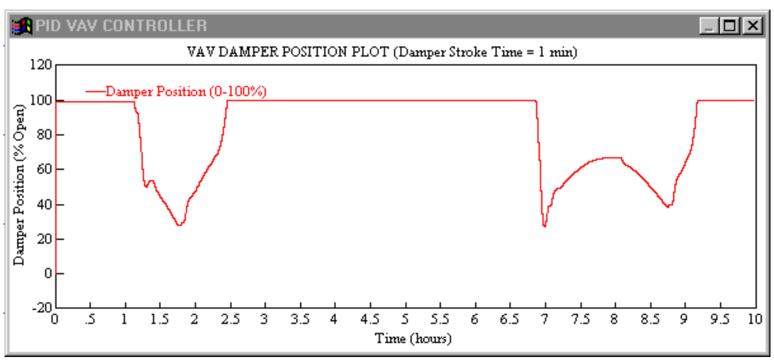

Figure 22. VAV damper response when supply air temperature is at 60 °F

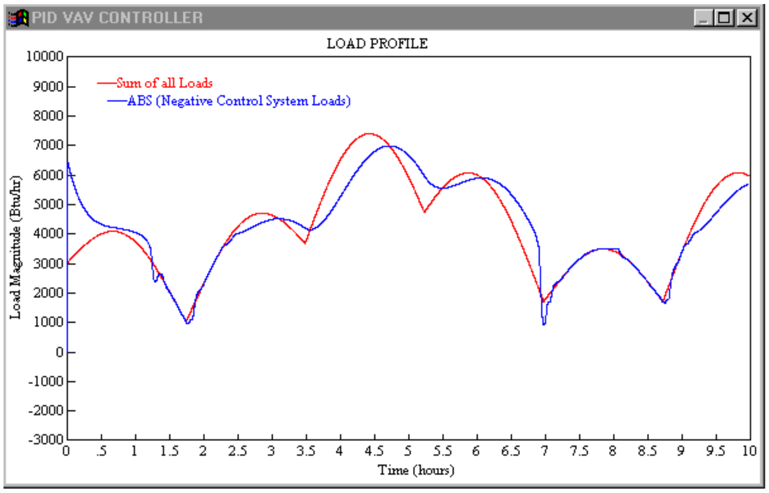

Figure 23. VAV load matching when supply air temperature is at 60 °F

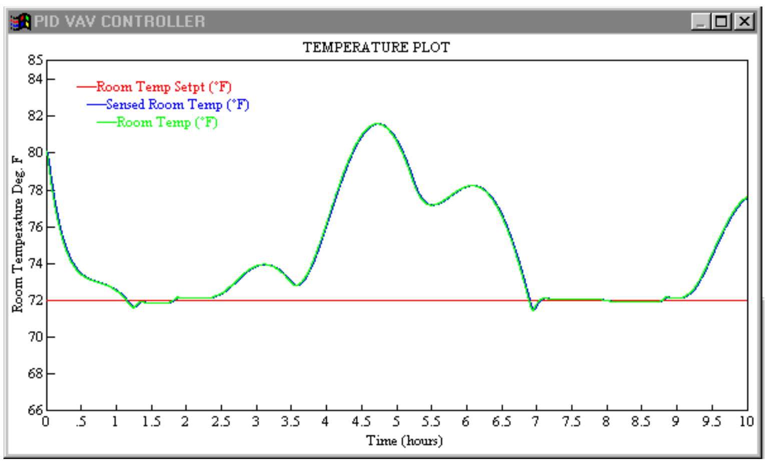

Figure 24. VAV temperature control when supply air temperature is at 60 °F

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