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Damper Authority Estimation and Adaptive Flow Control

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Abstract

Knowledge of the authority of control dampers in HVAC systems may be used for diagnostic purposes or to enhance control performance. In this paper, a method of estimating damper authority in air distribution systems is described. The method only requires measurements that are normally available in modern HVAC systems with digital controls. The method is based on a technique that allows the static pressure drop across a branch to be regulated even if that pressure is not measured. Experimental results on a Variable Air Volume (VAV) air handling unit demonstrate the efficacy of the method. A flow control strategy that uses feedforward compensation to eliminate the sluggish behavior of conservatively tuned feedback controllers is described. The algorithm is based on a quasi-equilibrium model of the flow characteristic and makes use of knowledge of the authority. The maximum flow rate, which is generally unknown, is estimated from position and flow rate measurements. Therefore the controller is adaptive. The feedforward commands are combined with feedback commands to ensure robust behavior in the presence of model uncertainty. Computer simulations demonstrate the improvements in control performance.

1. Introduction

Authority is a parameter of the final control elements (dampers or valves) in fluid distribution systems. It is normally described with reference to valves, but the concept also applies to dampers. Not all definitions of authority are identical. For example, in [1] authority is defined as the pressure drop across a valve when it is wide open divided by the total system pressure drop. In [2] authority is defined as the pressure drop across a valve when it is wide open divided by the pressure drop across the valve when it is controlling. A problem with both of these definitions is that the authority depends on the total system pressure drop, which varies with time.

Control engineers prefer a high authority because the flow is typically easier to control when the authority is high. A higher authority may be achieved with smaller dampers, shorter ducts, or fewer obstructions in the ducts. Increasing the authority reduces initial costs. But when it is achieved by reducing the damper size, operating costs increase because the total system pressure drop becomes higher. Therefore, the selection of authority (and damper size) at the design stage is a tradeoff between ease of control and operational cost. In [1] it is suggested that the authority should be greater than 0.5, while in [3] it is suggested that the authority should be between 0.25 and 0.33.

One benefit of being able to measure authority is that design or installation faults that will either make the system difficult to control or make the system inefficient may be detected during commissioning. The authority may also be affected over time by operational faults. For example, if a damper is in series with a heat exchanger, then the authority will change if the heat exchanger becomes fouled in a way that restricts the air flow. Therefore, an additional benefit is that certain operational faults may be detected if authority is monitored. A third benefit of measuring the authority is that it provides additional information about the system behavior that can be used to improve control performance.

In this paper, a method of estimating the authority of dampers in air distribution systems from flow, position, and pressure measurements is developed. First, a mathematical model of the behavior of a control damper is described. This model leads to the definition of an authority parameter which is nearly constant under a large range of normal operating conditions even though the total system pressure drop is not constant. The method is based on a technique which allows the static pressure drop across a branch to be regulated even if that pressure is not measured. Therefore the branch can be treated as a single-duct system with a constant pressure source. It is shown that this method can be applied to systems with at least one controlled pressure and that this method is insensitive to leakage. Experimental results on a VAV terminal unit demonstrate the efficacy of the method.

The performance of flow controllers in heating, ventilating, and air-conditioning (HVAC) systems is critical to the reliability, energy efficiency and overall performance of such systems. In variable-air-volume (VAV) terminal units, flow controllers are cascaded with zone temperature controllers to reject pressure disturbances in the air supply system. Under normal operation, the most important control performance metrics are good disturbance rejection and high reliability. However, during commissioning and manual troubleshooting, a fast response to setpoint changes is the most important control performance metric. Poor flow control performance in such systems may lead to reduced energy efficiency, degraded temperature control performance, premature mechanical failures or extended time spent on commissioning and troubleshooting. Flow controllers are also used to regulate the amount of fresh, outdoor air entering buildings. Like the flow controllers found in VAV terminal units, it is necessary that these controllers provide good setpoint tracking and disturbance rejection, and also be extremely reliable.

Typically, fixed-gain controllers are used to control flow. In order for the controllers to be robust, they must be tuned so that they are stable even under the highest-gain conditions of the damper or valve. This can lead to sluggish control performance when the ratio of the maximum to minimum gain is high. The primary nonlinearity in flow control loops with motorized actuation is the nonlinear relationship between the flow rate and the damper or valve position. This nonlinear relationship may cause the open-loop gain to vary over the operating range by an order of magnitude or more depending on the system design.

In this paper, a strategy for eliminating the sluggishness of fixed-gain flow controllers is described. The approach is to use feedforward compensation. This requires the use of a model of the process. Since the maximum flow rate of the damper or valve, which is a parameter of the model, cannot be measured and will vary with time it is estimated from flow and position measurements. Therefore, the feedforward compensation is adaptive.

In the next section, the behavior of a damper or valve, and the actuation system is described. A mathematical model of the flow characteristic is developed which is used to estimate damper authority and to compute feedforward position commands. The emphasis is on air flow control with dampers, but the method may be applied to valves and to other fluids.

2. Modeling

First the actuator dynamics are described. Then the inherent characteristic, authority and installed characteristic of a single damper in a duct is defined. Then the authority of a damper in a multi-branch distribution system is defined.

2.1. Actuator and Positioner

A positioner is a feedback loop for the actuator position. Positioners may be either analog or digital. Pneumatic actuators and DC motors often have analog positioners. Stepper motors have drivers that may operate on an analog position command. A detailed description of positioners for pneumatic actuators may be found in [4]. In subsequent sections, it is assumed that a positioner is present and that the position indication is available to a digital control system.

2.2. Incompressible Duct Flow

The analysis of the steady flow of an incompressible fluid in a duct may be found in any introductory text on fluid mechanics (e.g., [5]). The equation describing this flow is as follows:

$$\frac{p_1}{\rho g} + \frac{V_1^2}{2g} + z_1 = \frac{p_2}{\rho g} + \frac{V_2^2}{2g} + z_2 + K\frac{V^2}{2g} \tag{1}$$

where p denotes static pressure, ρ is the fluid density, g is the gravitational constant, V denotes the fluid velocity, z denotes head, K is the loss coefficient associated with frictional losses, or minor losses such as bends, obstructions, etc., and the subscripts denote the locations at the ends of the duct section. Since the density of air is low, gravitational energy is ignored in all subsequent sections.

When discussing authority, it is more convenient to use volume flow rates rather than air velocities. Ignoring gravitational energy, denoting the volume flow rate as, Q, and denoting the cross-sectional area as A, Equation 1 may be expressed in terms of volume flow rates as follows:

$$\frac{p_1}{\rho}+\frac{Q_1^2}{2A_1^2}=\frac{p_2}{\rho}+\frac{Q_2^2}{2A_2^2}+K\frac{Q^2}{2A^2} \qquad (2)$$

2.3. Inherent Characteristic

The inherent characteristic is the relationship between the flow rate and the damper position when the pressure drop across the damper is constant [6]. The inherent characteristic of a damper depends on whether or not the damper blades rotate in parallel or in opposition, on how the blades are constructed, and on how the seal in constructed.

With respect to Figure 1, the inherent characteristic is mathematically defined as

$$f_i \equiv \frac{Q}{Q_{max}} \qquad (3)$$

when $p_u - p_d$ is held constant.

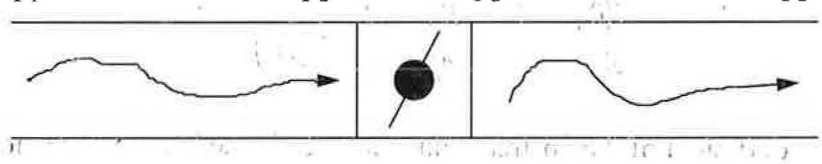

Figure 1: Schematic diagram of a duct section containing a single-bladed damper.

Using Equation 2, it can be shown that the inherent characteristic is as follows:

$$f_i(\theta)=\left(\frac{\frac{K_o}{A_u^2}+\frac{1}{A_d^2}-\frac{1}{A_u^2}}{\frac{K(\theta)}{A_u^2}+\frac{1}{A_d^2}-\frac{1}{A_u^2}}\right)^{\frac{1}{2}} \qquad (4)$$

where θ is the fraction of the fully open position, K_o is the loss coefficient in the fully open position, and the subscripts 'u and d, refer to locations just upstream and downstream of the final control element. When $A_u = A_d$,

$$f_i(\theta)=\left(\frac{K_o}{K(\theta)}\right)^{\frac{1}{2}} \qquad (5)$$

2.4. Installed Characteristic

If the pressure difference across a duct section such as that shown in Figure 1 is constant, then as the damper rotates, the pressure across the damper will vary due to changes in the pressure losses in the upstream and downstream sections of the duct. Therefore, the flow characteristic for the duct section will be different than the inherent characteristic of the damper, and it will depend on the pressure losses in the upstream and downstream duct sections. The characteristic of the duct and damper section is referred to as the installed (or system) characteristic.

In [6] the installed characteristic is defined by the relation between flow rate and position, regardless of the system pressure. In this paper, a slightly different definition is used. The installed characteristic is defined as the fraction of the full flow as a function of position when the system pressure is constant. Mathematically, the installed characteristic is defined as follows:

$$f_s \equiv \frac{Q}{Q_{max}} \tag{6}$$

when $p_1 - p_2$ is held constant. Combining Equations 2 and 6, the installed characteristic is as follows:

$$f_s = \left(\frac{\dfrac{K_o}{A_u^2} + \dfrac{K_u}{A_1^2} + \dfrac{K_d}{A_d^2} + \dfrac{1}{A_2^2} - \dfrac{1}{A_1^2}}{\dfrac{K(\theta)}{A_u^2} + \dfrac{K_u}{A_1^2} + \dfrac{K_d}{A_d^2} + \dfrac{1}{A_2^2} - \dfrac{1}{A_1^2}} \right)^{\frac{1}{2}} \tag{7}$$

where K_u is the loss coefficient of the upstream duct and K_d is the loss coefficient of the downstream duct. When all areas are equal, Equation 7 reduces to the following:

$$f_s = \left(\frac{K_o + K_u + K_d}{K(\theta) + K_u + K_d} \right)^{\frac{1}{2}} \tag{8}$$

Authority of dampers and valves has been defined by others in different ways. In [1,6] authority is defined as the pressure drop across a damper or valve when it is wide open divided by the total system pressure drop. In [2] authority is defined as the pressure drop across a valve when it is wide open divided by the pressure drop across the valve when it is controlling. By these definitions, the authority will vary with time because the total system pressure drop will be affected by the positions of other dampers in the system. In this paper, the authority is defined as the ratio of the pressure drop across the damper when fully open to the pressure drop across the branch it controls when fully open. Mathematically, the authority is defined as follows:

$$\alpha \equiv \frac{p_u - p_d}{p_1 - p_2} \qquad (9)$$

when the final control element is completely open (i.e., $\theta = 1$). It can be shown that

$$\alpha = \frac{\dfrac{K_o}{A_u^2} + \dfrac{1}{A_d^2} - \dfrac{1}{A_u^2}}{\dfrac{K_o}{A_u^2} + \dfrac{K_u}{A_1^2} + \dfrac{K_d}{A_d^2} + \dfrac{1}{A_2^2} - \dfrac{1}{A_1^2}} \qquad (10)$$

When all areas are equal, Equation 10 reduces to the following:

$$\alpha = \frac{K_o}{K_o + K_u + K_d} \qquad (11)$$

Note that the authority may be constant even if the loss coefficients K_u, K_o, and K_d are not constant. For example if the flow were laminar in all positions, then K_u, K_o, and K_d would be inversely proportional to the flow rate. If all areas were equal, then the flow rate terms would cancel in Equation 11, and the authority would be constant. Combining Equations 4, 7, and 10 yields the following relationship between the installed characteristic, the authority, and the inherent characteristic:

$$f_s = \left(\frac{1}{1 + \alpha \left(f_i^{-2} - 1 \right)} \right)^{\frac{1}{2}} \qquad (12)$$

In an air distribution system such as the one shown in Figure 2, an authority is defined for each branch. In other words, the pressure drop used to define authority is not generally dependent on the maximum system pressure. For example, the authority of damper 1 in Figure 2 is defined as

$$\alpha_1 \equiv \frac{p_{u1} - p_{d1}}{p_1 - p_{atm}} \qquad (13)$$

when damper 1 is completely open, but the authority of damper 2 is defined as

$$\alpha_2 \equiv \frac{p_{u2} - p_{d2}}{p_2 - p_{atm}} \qquad (14)$$

when damper 2 is completely open. The advantage of defining authority this way is that the authority is only dependent on pressure loss coefficients and only on those of the branch in which it is installed. Therefore, the authority will be nearly constant unless a system fault occurs such as a blocked diffuser. If the maximum system pressure drop were used to define the authority of each damper, then the authority of each damper would depend not only on the loss coefficients of other branches, but also on the positions and inherent characteristics of the other dampers.

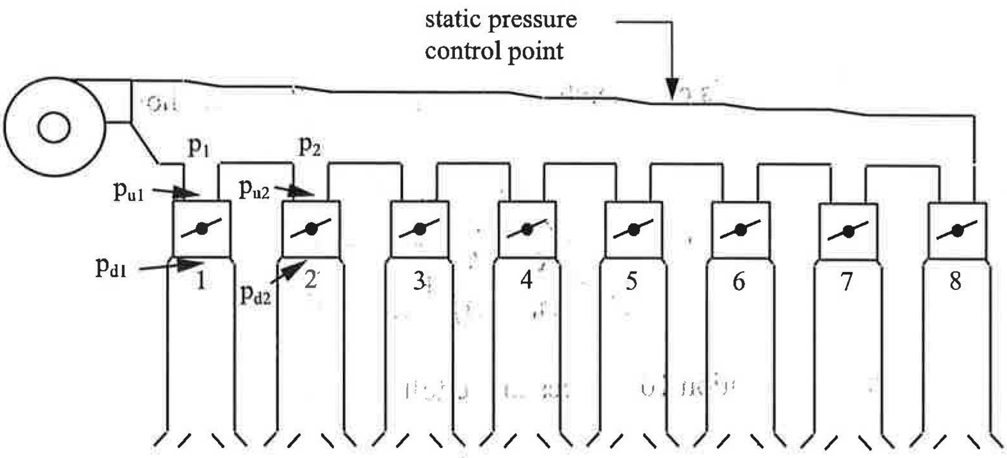

Figure 2: Schematic diagram of a VAV air distribution system with eight control dampers.

3. Authority Estimation

First, consider the duct section depicted in Figure 1, and assume that the volume flow rate and damper position can be measured, that the system pressure drop is constant but unknown, and that the authority is unknown. Combining Equations 6 and 12 yields the following relationship between the flow rate, the inherent characteristic, and the authority:

$$Q_{max}^2 + \alpha\left(1 - f_i^{-2}\right)Q^2 = Q^2 \tag{15}$$

The maximum flow rate is a function of the unknown pressure drop across the branch, so it is an unknown, but constant parameter of the duct section. Equation 15 is a linear regression on the unknown parameters α and Q_{max}^2. By moving the damper to two different positions and measuring the flow rate, one can solve a linear set of two equations for the two unknowns, α and Q_{max}^2.

Now re-consider the system depicted in Figure 2 in which the system consists of a single main with dampers controlling each of the branches. Like the single duct section described above, assume that the flow rate through each damper and the position of each damper can be measured. The pressure at the control point will be denoted as p_c.

First consider branches upstream of the control point. If the dampers downstream of the pressure control point are controlled so that the total flow rate past the pressure control point is constant, then since p_c is constant, the static pressure at branch point number 5 will be constant regardless of the flow rate through branch number 5 or any of the other branches upstream of number 5. Therefore, under these conditions branch 5 will behave in such a way that Equation 15 can be used to estimate the branch authority and the maximum flow rate through the branch under these conditions. Now if the flow rate through branch number 5 is held constant, then the static pressure at branch point number 4 will be constant, and the same procedure may be applied to branch number 4. This technique may be applied to all the remaining upstream branches. Note that the flow rate through branch 5 need not be controlled with a feedback controller. If the damper is held in a fixed position, then the flow rate through the branch will be constant because the pressure at the branch point will be constant.

Now consider the branches downstream of the pressure control point. Since the pressure at the control point is constant, the pressure at branch point number 6 will be constant if the flow rate past the pressure control point is constant. In order to use Equation 15 to determine the authority of branch 6, the position and flow rate of damper 6 must be adjusted. This will alter the flow rate past the control point unless the flow rate through one or more of the other branches downstream of branch 6 is adjusted to compensate for the experiment on branch 6. Therefore, to determine the authority of branches downstream of the pressure control point, the flow rate(s) along the main from the pressure control point to the branch to be tested must be held constant by appropriately controlling one or more of the branches downstream of the branch to be tested. The exception is the last branch. To determine the authority of the last branch, the second to last branch must compensate for the changes in the flow rate during the test.

The advantage of this method is that it is insensitive to leakage. To see this, assume that when testing branch 4 there is leakage Q_L between branch points 4 and 5 through a hole with a loss coefficient K_L. Since the pressure at branch point 5 is constant, the pressure at the hole is constant, so Q_L is constant. This implies that the flow rate between branch point 4 and the hole is constant, and thus the pressure at branch point 4 is constant. This same argument applies to leakage at other points in the system.

The disadvantage of this method is that it cannot generally be performed from data acquired during normal operation. Instead, it must be performed during commissioning or during times when the normal system operation can be interrupted, much as a step test is used to determine controller parameters. The authority of each damper, once determined, will only change if a loss coefficient in the branch changes. This could happen if balancing dampers are moved, if a duct becomes blocked, or if a heat exchanger fouls considerably. Periodic authority estimation can be used to detect these faults.

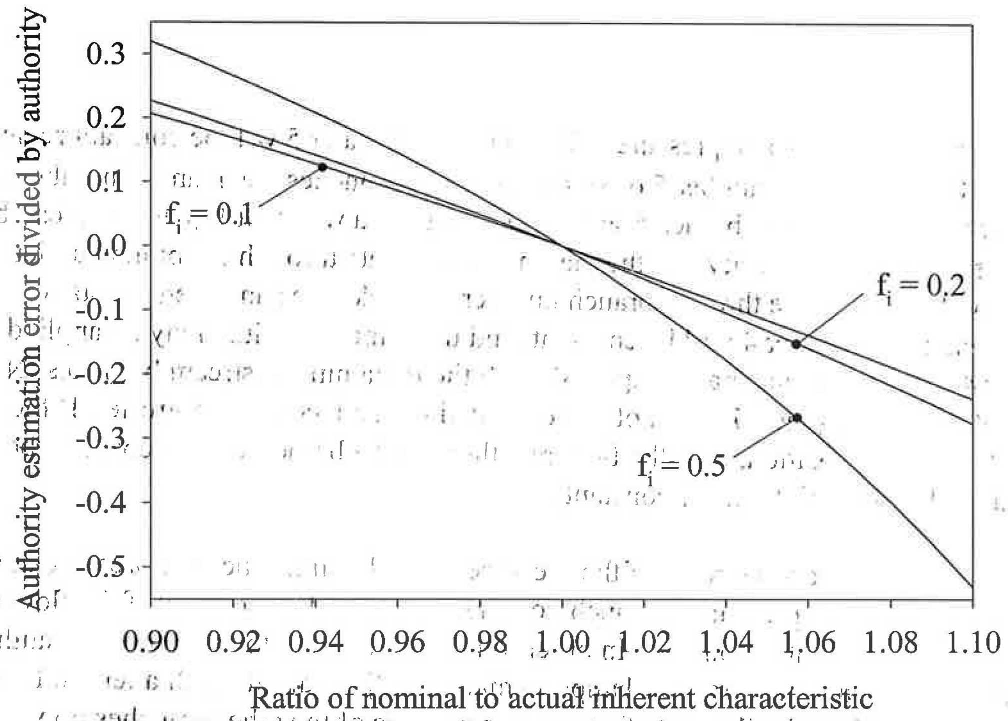

Figure 3: The effect of an error in the nominal inherent characteristic on an estimate of the authority.

The method described in this section requires that the inherent characteristic be a know function of the position. In practice there will be some uncertainty in the nominal inherent characteristic, even when testing a damper that has been carefully characterized. In order to gain some insight into how errors in the nominal inherent characteristic affect estimates of the authority, assume that the authority is estimated using Equation 15 and measurements taken at two positions: fully open and at some partially open position. Also assume that there is no uncertainty in the flow rate measurement. When the damper is fully open, the inherent characteristic is equal to one by definition, so the uncertainty in the estimated authority under these conditions is solely a function of the uncertainty in the inherent characteristic at the partially-open position. It can be shown that under these conditions the authority estimation error is related to the error in the inherent characteristic as follows:

$$\frac{\alpha - \hat{\alpha}}{\alpha} = \frac{1 - c^2}{1 - c^2 f_i^2} \tag{16}$$

where α is the actual authority, $\hat{\alpha}$ is the estimated authority, f_i is the actual value of the inherent characteristic in the partially-open position, and $c = f_i / f$ is the ratio of the nominal (estimated) value of the inherent characteristic in the partially-open position to the actual inherent characteristic at that position. This relationship is shown graphically in Figure 3. In order to reduce sensitivity to an error in the nominal inherent characteristic, the low-flow data point should be at a position where the inherent characteristic is 0.2 or less. Using more than two measurement points will change the relation between the authority estimation error and the inherent characteristic errors, and it will reduce the sensitivity to inherent characteristic errors.

4. Experimental Results

In this section, results of applying the authority estimation method described above to a branch of a variable-air-volume system are described. The system is constructed as in Figure 2. There are eight branches, each containing a control damper. The static pressure control point is just downstream of branch number five. The authority of the damper in branch number three was estimated. At branch point number three, the main has a square cross-section, 0.6096 meters on each side. Each VAV box, which contains a control damper, is mounted directly to the main. The VAV box is constructed of a round throat section attached to a square housing for the damper. The round throat is 0.254 meters in diameter and 0.254 meters long. It contains the differential pressure pickup used by the DDC system to control the flow rate. The square housing is 0.3429 meters on each side. The polymeric seals for the damper are attached to the inside of the square housing. The branch has a square cross-section that is 0.381 meters on each side.

During the experiment, the static pressure at the control point was regulated to 248.8 Pa. The flow rates through all of the branches other than number 3 were controlled to a fixed level during the test. The position of the damper was commanded by a digital control system, and was measured with a protractor attached to the actuator and a needle attached to the damper shaft. After the static pressure reached equilibrium, the flow rate through the branch, the static pressure in the main at the branch point, and the differential pressure across the VAV box were recorded. The flow rate through branch number 3 was measured at the diffuser with a commercially available flow capture hood. The static pressure in the main was measured at the centerline of the branch point. The differential pressure was measured with the static pressure tap in the main and a second static pressure tap at the point where the branch duct attaches to the VAV box adapter. The loss coefficient at each damper position was computed using the following equation:

$$K = \left(\frac{2\Delta p}{\rho Q^2} - \frac{1}{A_d^2} + \frac{1}{A_u^2} \right) A_u^2 \tag{17}$$

where Δp is the pressure drop across the VAV box, A_u is the area of the throat of the VAV box (0.0507 m^2) and A_d is the area of the branch duct (0.1452 m^2). Note that this loss coefficient contains the entrance pressure loss into the branch from the main. To account for this additional loss, the authority is computed as follows:

$$\alpha = \frac{\Delta p}{p_{main}} \tag{18}$$

when the damper is fully open, and where p_{main} is the static gauge pressure of the main at the branch point. The inherent characteristic at each position was computed using Equation 4, the calculated pressure loss coefficients, and the upstream and downstream areas.

Table 1 shows the recorded data and the values of the loss coefficients and the inherent characteristic at each position. The pressure readings indicate some measurement inaccuracy because at the first and second positions, the difference between p_{main} and Δp cannot be recovered by converting the dynamic pressure to static pressure. However, the measurement error is small (on the order of 10 Pa or 5% of the reading), so it is ignored.

Table 1: Recorded and calculated values from the experiment.

θ, ND	Q, m^3/s	p_{main}, Pa	Δp, Pa	K, ND	f_i, ND
0	0.0411	275.91	281.39	739.14	0.0496
0.2951	0.2723	275.91	283.58	17.828	0.3272
0.6557	0.5074	271.56	258.42	5.3266	0.6388
1	0.7203	270.46	212.48	2.6931	1

The maximum flow rate and authority are computed by solving a least squares problem based on Equation 15 using the data and calculated values at the four positions. The estimated values are:

$$\alpha = 0.7429$$
$$Q_{max} = 0.7242 \text{ m}^3/\text{s}$$

The measured value of α computed from Equation 18 is:

$$\alpha = 0.7856$$

and the measured maximum flow rate is shown in Table 1. The differences between the measured and estimated values of the authority and maximum flow rate are 5.44% and 0.54%, respectively.

5. Adaptive Flow Control Strategy

Figure 4 shows a block diagram of the control algorithm. A feedforward position command is computed from the flow setpoint based on a model of the flow characteristic. The estimate of the maximum flow rate is modified at each step to reflect changes in the static pressure drop across the duct section controlled by the damper. The feedforward command and the feedback position change commands are used to determine the position command to the positioner. The rest of this section describes the function and design of each of the blocks in Figure 4.

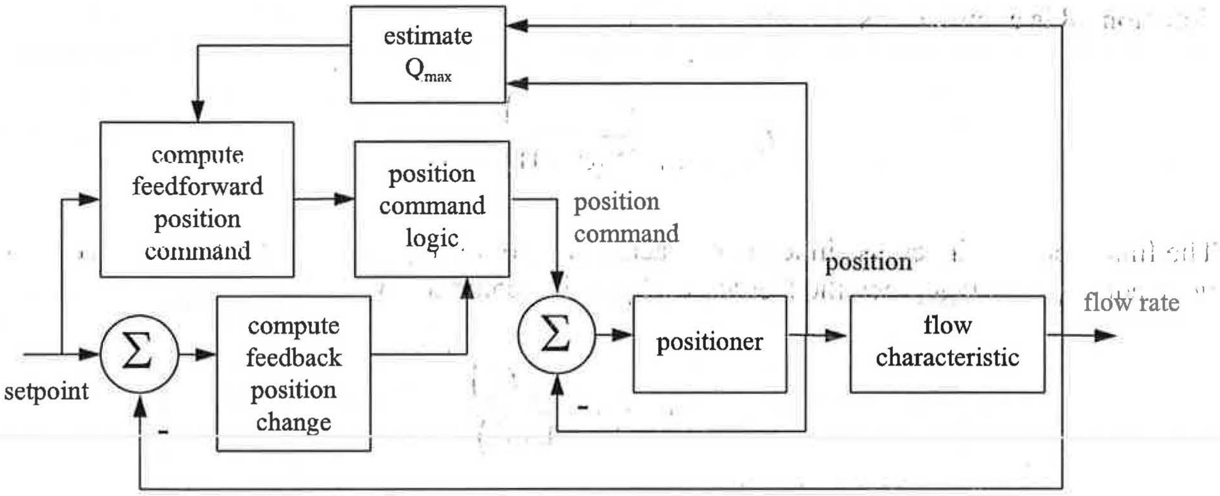

Figure 4: Block diagram of the adaptive feedforward plus feedback strategy.

5.1. Parameter Estimator

The purpose of the parameter estimator is to estimate the maximum flow rate through the duct section. The maximum flow rate is proportional to the square root of the unknown pressure drop across the controlled duct section

$$Q_{\max} = \left(\frac{p_1 - p_2}{\rho\left(K_o + K_u + K_d\right)} \right)^{\frac{1}{2}} \tag{19}$$

and is unknown because $p_1 - p_2$, K_o, K_u, and K_d are unknown. Since the pressure will change with time, the maximum flow rate will change with time. Assuming that the authority is known from a procedure such as that described in Section 4, the maximum flow rate just after discrete time k can be estimated using the following filter:

$$\hat{Q}^2_{\max}\left(k^+\right) = (1-w)\hat{Q}^2_{\max}\left(k^-\right) + wQ^2(k)\left(1 - \alpha + \alpha f_i^{-2}(k)\right)^{\frac{1}{2}} \tag{20}$$

where w is a free design parameter. The inherent characteristic must be known to estimate the maximum flow rate using Equation 18.

5.2. Feedforward Command

Computing the feedforward position command consists of three steps. First the value of the installed characteristic that corresponds to the flow setpoint is computed using the estimated maximum flow rate as follows:

$$f_{s_{ff}} = \frac{Q_{sp}}{\hat{Q}_{\max}} \tag{21}$$

Next, the inherent characteristic corresponding to the installed characteristic computed with Equation 18 is computed as follows:

$$f_{i_{ff}} = \left(\frac{\alpha f_{s_{ff}}^2}{1 + f_{s_{ff}}^2 (\alpha - 1)} \right) \tag{22}$$

The final step is to invert the inherent characteristic. For example, if the inherent characteristic were equal-percentage, then the feedforward position command would be computed as follows:

$$\theta_{ff} = 1 - \frac{\ln\left(f_{i_{ff}}\right)}{\ln\left(f_c\right)} \tag{23}$$

where, in theory, f_c is the value of the inherent characteristic in the fully-closed position. In practice, final control elements that are nominally equal-percentage have a value of f_i in the fully-closed position that is often less than f_c.

5.3. Feedback Change Command

The feedback controller computes a feedback change command that is proportional to the difference between the setpoint and the measured flow rate as follows:

$$\Delta\theta_{fb} = G_{fb}\left(Q_{sp} - Q\right) \tag{24}$$

The value of G_{fb} must be chosen so that the feedback controller is stable at any damper position.

5.4. Position Command Logic

The feedforward position command and the feedback position change command are combined using the following logic:

If	$\operatorname{sgn}\left(\theta_{ff}(k) - \theta_{ff}(k-1)\right) = \operatorname{sgn}\left(\Delta\theta_{fb}(k)\right)$
Then	$\Delta\theta_c(k) = \max\left[\theta_{ff}(k) - \theta_{ff}(k-1), \Delta\theta_{fb}(k)\right]$
Else	$\Delta\theta_c(k) = \Delta\theta_{fb}(k)$

In words, when the sign of the change in the feedforward command is the same as the sign of the feedback change command, then the position command is the maximum of the two. Otherwise it is the feedback change command. This logic prevents the feedforward command from fighting the feedback command but allows for larger movements than feedback alone would provide when the larger movements are warranted by a sudden setpoint change or disturbance.

6. Computer Simulations

In this section, the behavior of the adaptive feedforward flow control strategy is demonstrated with computer simulations and is compared to a fixed-gain feedback control strategy.

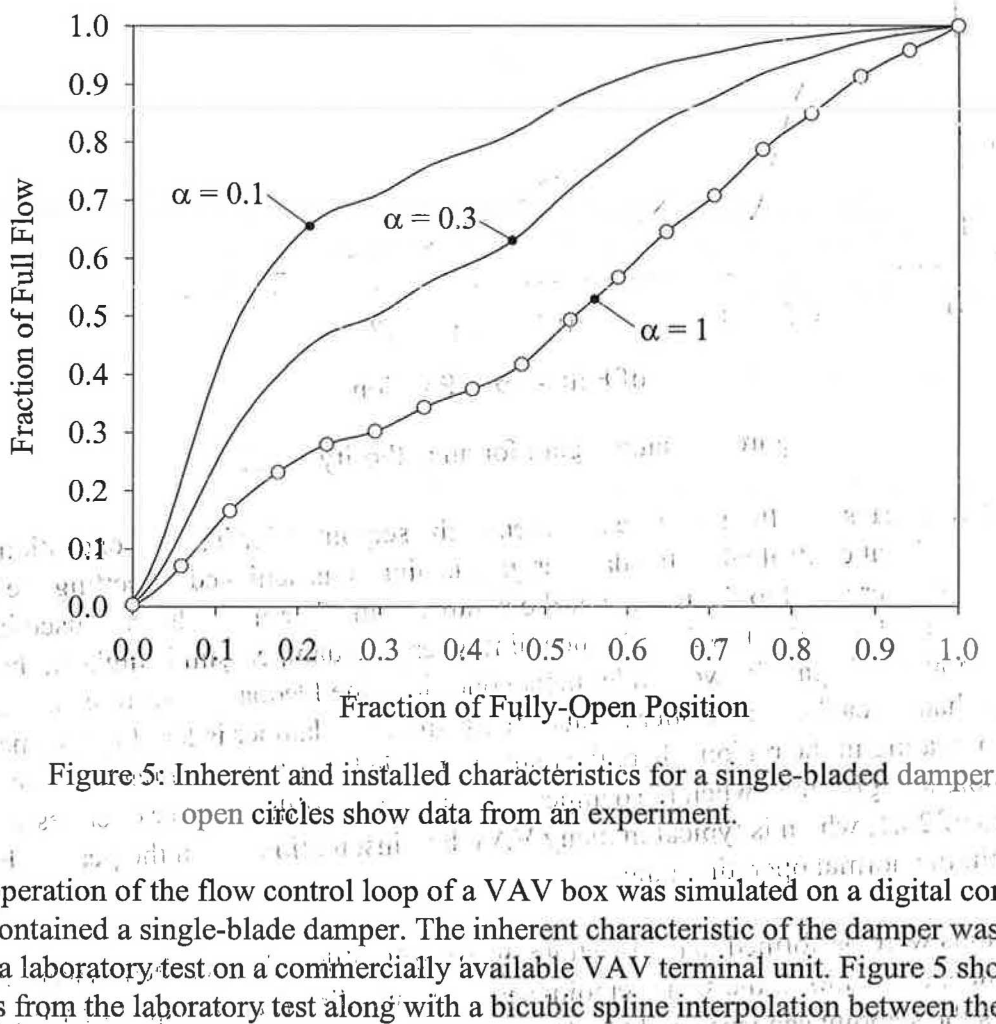

Figure 5: Inherent and installed characteristics for a single-bladed damper. The open circles show data from an experiment.

The operation of the flow control loop of a VAV box was simulated on a digital computer. The box contained a single-blade damper. The inherent characteristic of the damper was determined from a laboratory test on a commercially available VAV terminal unit. Figure 5 shows the data points from the laboratory test along with a bicubic spline interpolation between the points. The open-position pressure loss included that from the differential pressure array, a flow straightener installed in the box by the manufacturer, and the losses due to the changes from a round to rectangular geometry and back. Figure 5 also shows the installed characteristic when the authority is 0.3 and 0.1. According to [3] the authority should be between 0.25 and 0.33. However, VAV boxes are commonly over-sized, which lowers the authority. In the simulations described below, the authority was 0.1.

The adaptive feedforward controller was compared to a fixed-gain feedback controller that was designed to achieve deadbeat control performance when the gain of the damper is highest. The gain of the damper is proportional to the slope of the installed characteristic. Figure 6 shows the slope of the damper characteristic of Figure 5. The maximum slope is 4.7 and the ratio of the maximum slope to the minimum slope is 66.

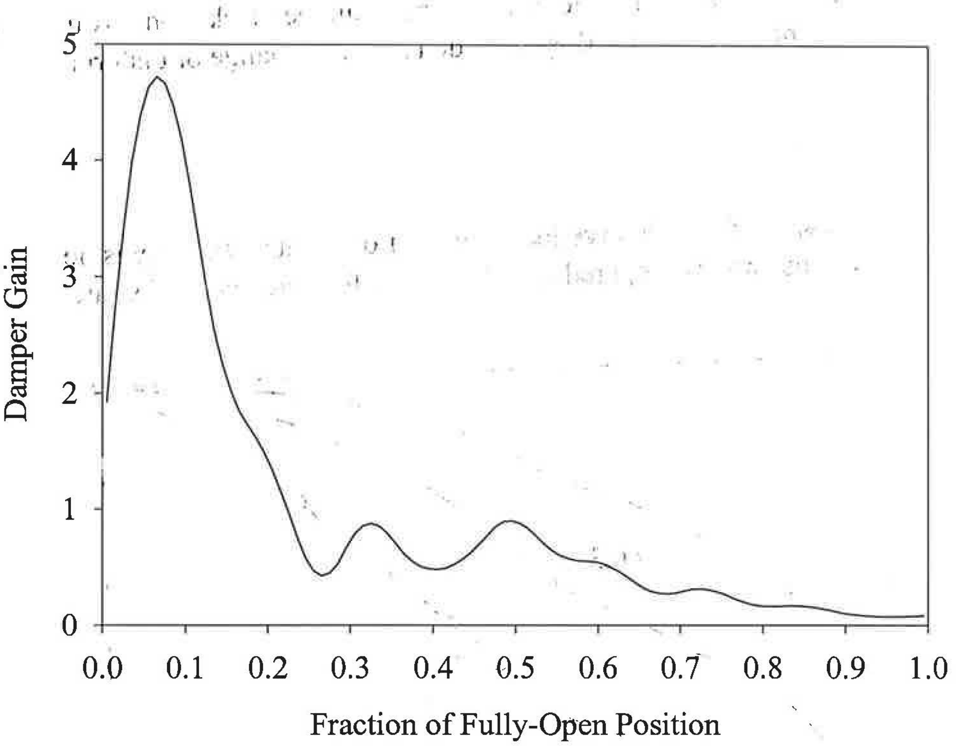

Figure 6: Damper gain for an authority of 0.1.

Deadbeat control means that the flow rate is driven to the setpoint after just one execution of the control loop. Deadbeat control when the damper gain is highest is achieved by setting the gain of the feedback controller equal to the inverse of the damper gain. Therefore, the gain used in the simulations described below was 0.212. At the point where the damper gain is highest, the stability margin with this gain is two. Under most conditions the feedback controller will be more sluggish than a deadbeat controller because the gain of the damper is less than its maximum value. When operating in the region where the damper gain is lowest, the feedback controller will be 66 times more sluggish than when the damper gain is highest. If the damper operates with a turndown ratio of 20:1, which is typical in many VAV box installations, then the peak in Figure 5 will lie within the normal operating range.

Three simulations were performed to demonstrate the benefit of the adaptive feedforward control action. In all three simulations, the same setpoint sequence and disturbance sequence were used. Figure 7 shows the setpoint sequence and the Q_{max} sequence for the three simulations. A change in Q_{max} is equivalent to a change in the static pressure at the branch point in the main duct. In the first simulation, there is no noise, no modeling error, and the parameter tracking gain was high ($w = 1$). This is the best-case scenario for reaping a benefit from the feedforward compensation. Figure 8 shows a comparison of the feedforward plus feedback and feedback-only control strategies under these conditions. The feedforward plus feedback strategy provides deadbeat

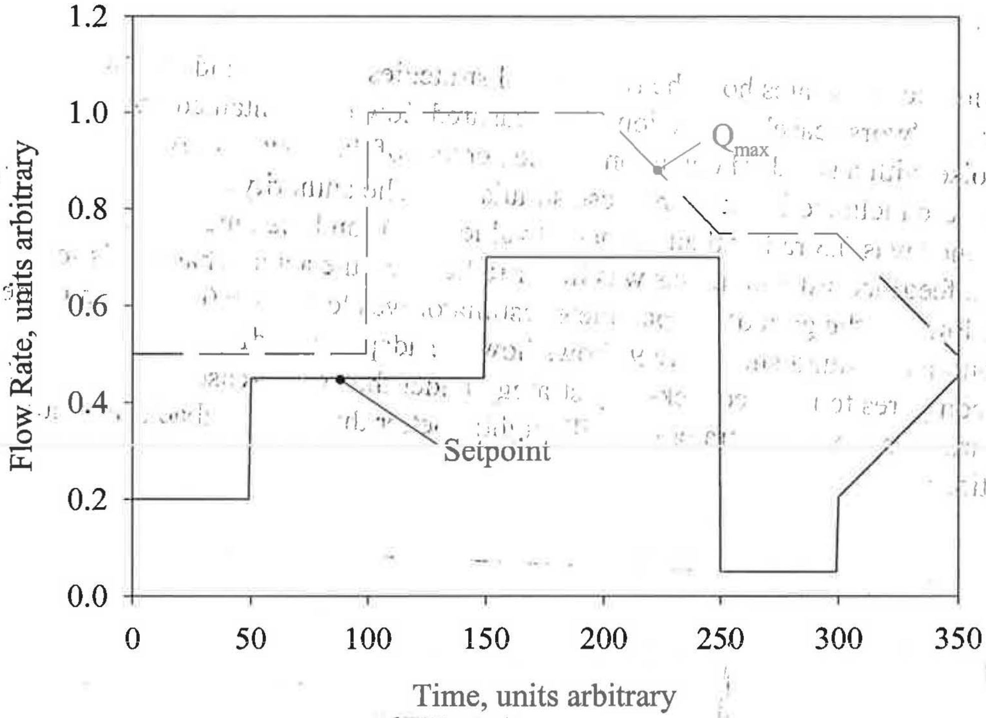

Figure 7: Setpoint and Qmax used in the simulations.

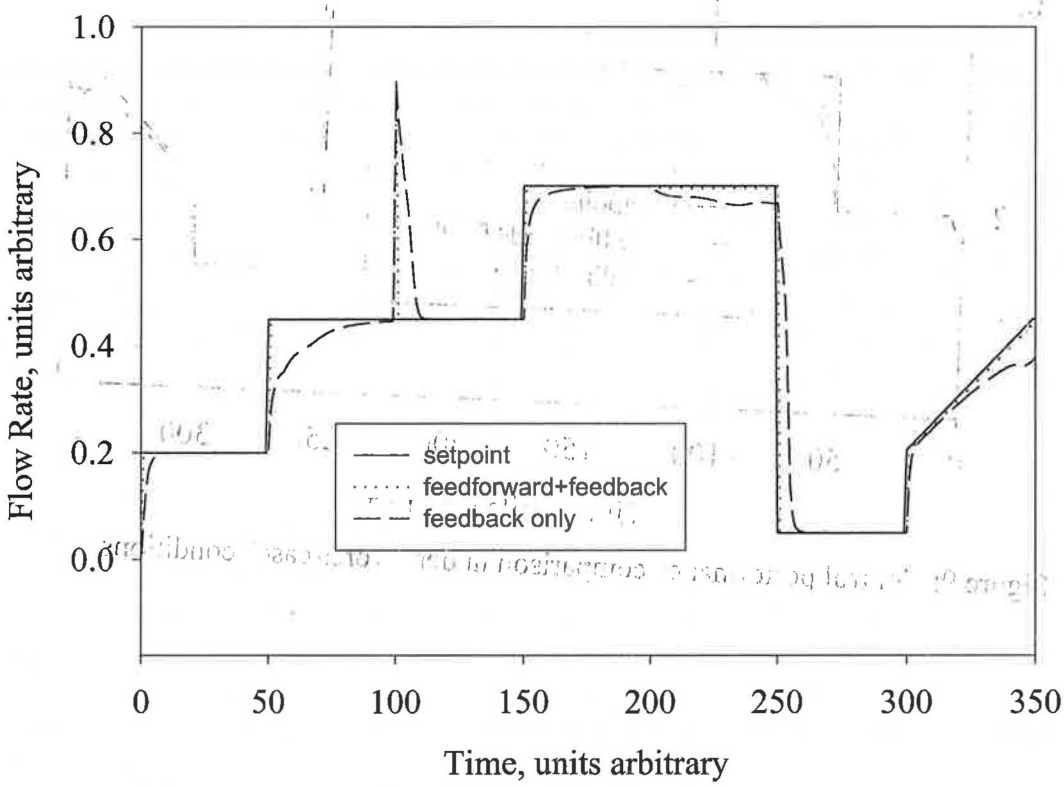

Figure 8: Control performance comparison under "best-case" conditions.

setpoint tracking and deadbeat disturbance rejection. From the figure it is clear how the gain of the damper affects the performance of the feedback-only strategy. When the flow rate is a large fraction of the maximum flow rate, the feedback-only strategy is much less effective at tracking the setpoint and rejecting the disturbance than when the flow rate is a small fraction of the maximum flow rate.

The second simulation demonstrates how the two control strategies compare under a "worst-case" situation. For the "worst-case" simulation, the measured flow rate contained normally-distributed white noise with a standard deviation of one percent of the flow rate. Also two kinds of modeling errors were included in the worst-case simulation. The authority used to compute the feedforward commands was 0.3 rather than the actual value of 0.1, and the inherent characteristic used to compute the feedforward commands was linear rather than the actual characteristic shown in Figure 5. Finally, the gain of the parameter estimator was low ($w = 0.1$) which made the feedforward commands sluggish. Figure 9 shows how the adaptive feedforward plus feedback strategy compares to the feedback-only strategy under the "worst-case" conditions. The adaptive feedforward plus feedback strategy is still slightly better than the feedback-only strategy under these conditions.

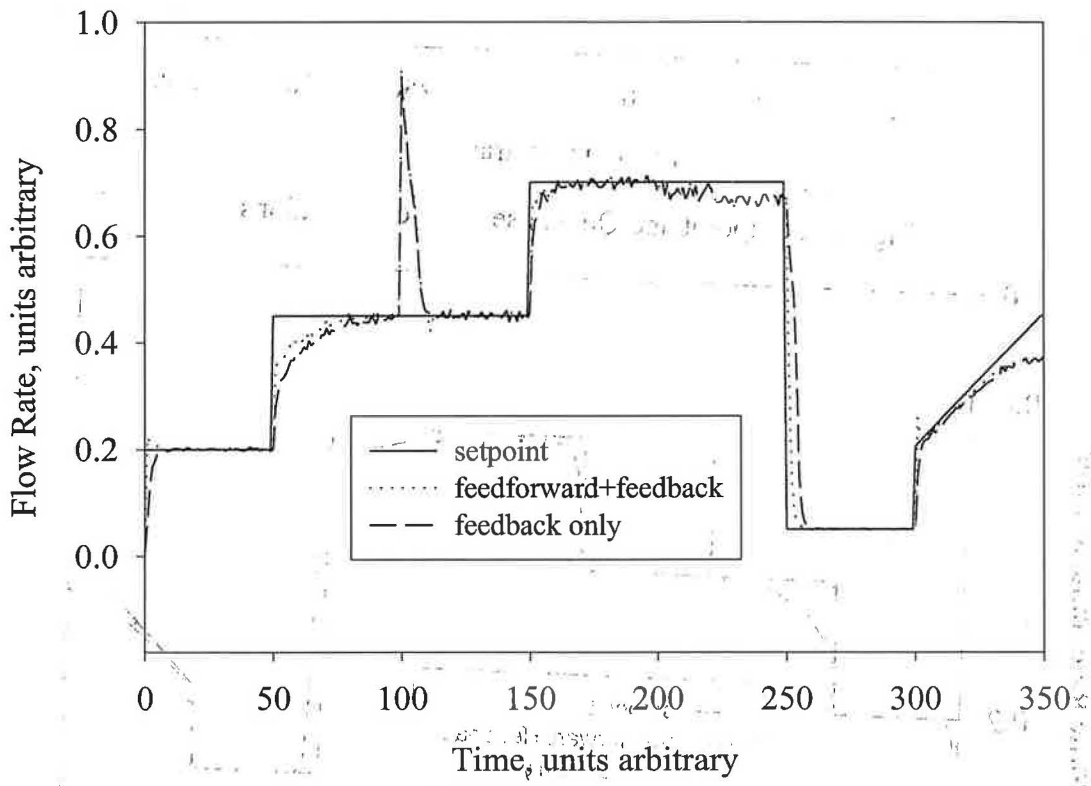

Figure 9: Control performance comparison under "worst-case" conditions.

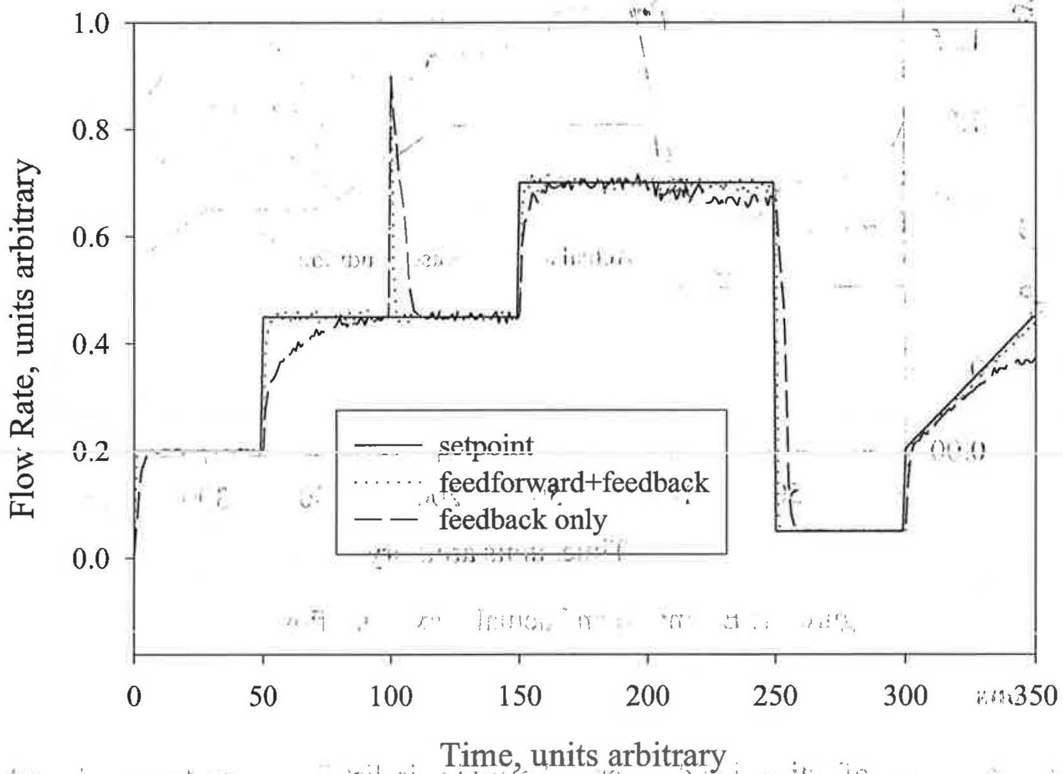

Figure 10: Control performance comparison under "typical" conditions

The third simulation demonstrates how the two control strategies compare under a "typical" situation. For the "typical" simulation, the measured flow rate contained normally-distributed white noise with a standard deviation of one percent of the flow rate, and the authority used to compute the feedforward commands was 0.2 rather than the actual value of 0.1. The gain of the parameter estimator was high ($w = 1$) which improves the response time. Figure 10 shows how the adaptive feedforward plus feedback strategy compares to the feedback-only strategy under the "typical" conditions. The adaptive feedforward plus feedback strategy is significantly better at both setpoint tracking and disturbance rejection than the feedback-only strategy under these conditions. Part of the improved response is due to the high gain of the parameter estimator. By setting $w = 1$, additional measurement noise is introduced into the control loop. This has the undesirable effect of increasing the standard deviation of the position signal by 34% during "steady-state" conditions. A tradeoff between actuator motion and control performance could be achieved by using a lower value of w.

Although the objective of the control system is to keep the flow rate as close as possible to the setpoint, one may also be interested in how accurately the maximum flow rate is estimated. Figure 11 shows the estimated and actual maximum flow rates for the three cases described above. Under the "best-case" conditions, the estimated values are nearly indistinguishable from the actual values. However, under the "worst-case" conditions, there are large and persistent errors in the estimates. Even under the "typical" conditions, there are large and persistent errors. Improved control performance does not imply accurate parameter estimates.

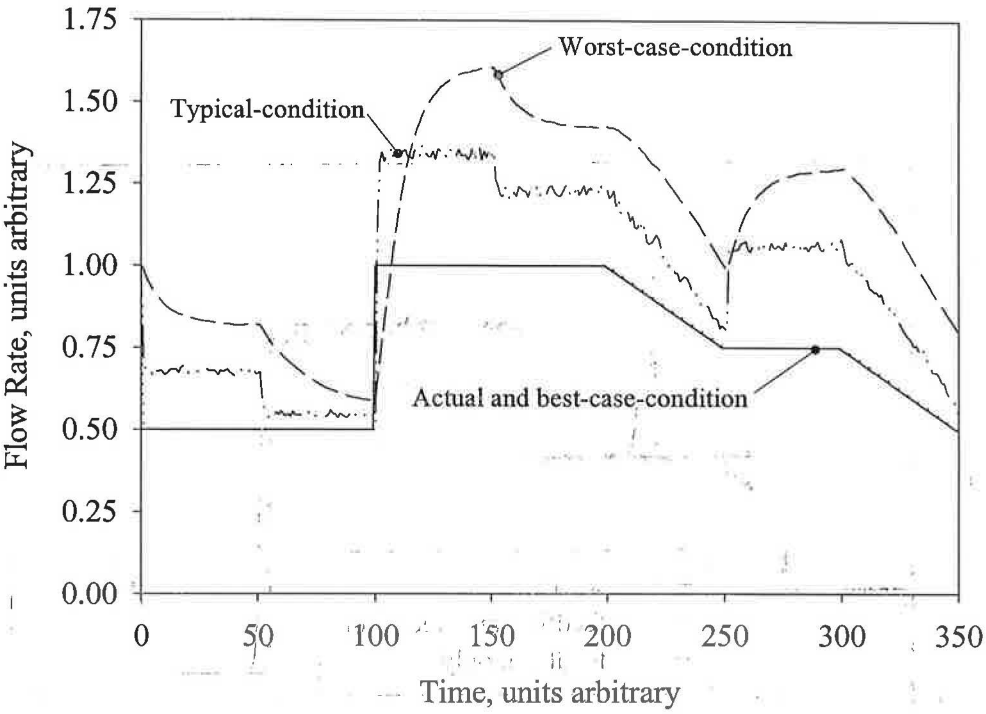

Figure 11: Estimated and actual maximum flow rate.

7. Conclusions

In this paper, a method of estimating damper authority in air distribution systems is described. The method only requires measurements that are normally available in modern HVAC systems with digital controls. The method is based on a definition which renders the authority a nearly constant parameter and on a technique which allows the static pressure drop across a branch to be regulated even if that pressure is not measured. It is shown that the method is insensitive to duct leakage. Experimental results on a Variable Air Volume (VAV) air handling unit demonstrate the efficacy of the method.

Additionally, an adaptive flow control algorithm is described. The algorithm is based on a quasi-static model of the installed characteristic of the control damper and duct which uses the value of the known or estimated authority. A feedforward position command is computed based on the flow setpoint. The maximum flow rate, which is an unknown parameter of the model, is continually estimated based on position and flow information , so the feedforward commands are adaptive. The algorithm provides significant improvement in control performance over the best feedback-only strategy even in the presence of noise and modeling errors.

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