The Use of Simulation Data to Design Rule-based Controllers for HVAC Systems

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Me design of a fuzzy rule-based controller for the mixing-box of an air-handling unit is used to demonstrate how data obtained by computer simulation can be used to generate the rules. The controller uses measurements of the return and fresh air temperatures, together with the pressure drops across the dampers, to calculate values for the actuator control signals which determine the position of the dampers. The paper explains the methods used to generate the rules, discusses the choice of fuzzy reference sets and describes the approach used to produce suitable training data. The rule-based controller is implemented in a prototype version of the outstation of a new type of building energy management system which has a dedicated knowledge-based system capability. The performance of the controller is assessed using a building emulator which simulates the dynamic operation of an air-handling unit. Results are presented which illustrate the performance of the controller for both large and small differences in the return and fresh air temperatures, for a wide range of desired supply air temperatures and for different Jan speedy.

Introduction

Rule-based control has advantages in applications where it is difficult to obtain an accurate representation of plant behaviour using linear quantitative models. The main problem associated with the design of rule-based controllers is the difficulty of acquiring a complete and consistent set of rules. Data obtained by computer simulation can be used to generate the rules as an alternative to using rules based on expert knowledge. The design of a rule-based controller for the mixing-box in an air-handling unit is used to demonstrate the technique.

Satisfactory control of the mixing box is essential if economizer [Park et al, 1984], ventilation [Mumma and Wong, 1990] and pollution [Knoespel et al, 1991] control systems are to operate correctly. Although the cooling-coil, the preheating coil and the mixing-box have very different operating characteristics, it is common for a single Proportional-plus-Integral controller cascaded with an output sequencer to be used to operate all three items of plant. The main problem associated with such conventional control schemes arises from the difficulty of tuning the supply air temperature controller so as to ensure stability over the full operating range of the air-handling unit. Even the control of the mixing-box itself can be problematic since individual dampers are often oversized and have different and non-linear installed characteristics [Dickson, 1987]. The large variation in the gain of the mixing-box, as the return and fresh temperatures change, introduces a further complication. Fuzzy rule-based control, based on qualitative descriptions of the behaviour of the plant, can deal with the

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non-linearities and take account of the inherent uncertainty and imprecision associated with the behaviour of a particular mixing-box.

Rule-based Control of the Mixing Box

The controller uses measurements of the return and fresh air temperatures, and the pressure drops across the dampers, to calculate values for the actuator control signals which determine the position of the dampers. A receding-horizon control strategy is used, based on a fuzzy model of the behaviour of the mixing-box. The fuzzy model consists of sets of fuzzy rules. One set of rules relates the required inlet, return and exhaust air fractions to the desired supply temperature and measured values of the return and fresh air temperatures. Other sets of rules relate the actuator control signals associated with each of the three sets of dampers to the desired air flow rates and the differential pressures across the dampers. Additional rules may be required to compensate for hysteresis in the actuator linkage (the flow through oversized dampers is particularly sensitive to damper position when the dampers are nearly closed), to take account of the rate-limit imposed by motor-driven actuators, to ensure adequate ventilation, and to specify the required exhaust air flow.

The rules that relate the temperatures to the air flow fractions are generated from data obtained by simulation based on a simple generic model of the mixing process. The rules that relate the damper position to the air flow rate and the differential pressure are generated from data obtained by experimental calibration of the dampers.

Calibration of the Dampers

The steady-state behaviour of the dampers is defined by the values of the blade angle, the air flow through the dampers and the differential pressure across the dampers, at a number of operating points. The test facility used to calibrate dampers consists of a set of dampers connected to a fan and inlet duct in which the air flow is measured. A commercial motor-driven actuator is used to position the dampers. The actuator takes 94 seconds to move from its fully open to fully closed position, and has hysteresis equivalent to 2.75% of full span. A multi-variable control scheme, based on the use of low gain PI controllers, is used to maintain the dampers at the desired operating points [Hawkins, 1992] which are distributed over the specified operating range.

Fig. 1 shows the results of typical calibration tests. The data presented here have been obtained from a computer simulation of the damper calibration rig.

Generation of Fuzzy Rules from Calibration Data

A method of fuzzy identification based on "fuzzy reference sets" [Postlethwaite, 1991] is used to generate the rules. Flow, differential pressure and damper position reference sets are first defined. The flow and pressure sets are chosen to cover the calibration range and are evenly distributed. With the exception of the outermost sets, triangular membership functions are used for both the pressure and flow sets (see Fig. 2) so as to provide a smooth transition between calibration points and avoid abrupt discontinuities in the rules being fired. The membership functions overlap by 50% so that a value of flow or differential pressure will lie within two fuzzy sets unless it happens either to lie exactly on a calibration set-point, or to lie far outside the calibration range. The apex of each membership function is positioned to coincide with the operating points used during calibration. The damper sets are fuzzy singletons positioned according to the 8 bit integer value that specifies the damper position which was obtained from the calibration. The sets that are used in the rules are labelled D0 to D39 in order.

The credibility of each rule is calculated from a measure of the extent to which the data at each calibration point are members of the fuzzy sets associated with the antecedent of the rule. If the desired operating point is achieved exactly, the associated rule will correctly relate the pressure and flow sets to the damper angle and the credibility of the rule is unity. Where the calibration point and the operating point actually achieved are different, the relationship between the pressure and flow sets and the damper angle suggested by the associated rule will be incorrect and the credibility will be less than unity. The credibility of the rule,

IF "DeltaP is P_j " AND "FlowDes is F_k "

THEN "Udamp is D_i "

is given by

$$R_{i,j,k} = \bigcup_{n=0}^{N} \min [\mu_{D_i} , \mu_{P_j} , \mu_{F_k}]_n$$

where the degrees of membership of D_i , P_j and F_k for the nth data set are

$$[\mu_{D_i} , \mu_{P_j} , \mu_{F_k}]_n$$

and N is the total number of data sets. Three of the forty rules generated from the calibration data are shown below :

IF "DeltaP is PSEVEN"
  AND "FlowDes is FTWO"
    THEN "Udamp is D33" (Credibility = 1.0)

IF "DeltaP is PEIGHT"
  AND "FlowDes is FTWO"
    THEN "Udamp is D34" (Credibility = 0.985)

IF "DeltaP is PTHREE"
  AND "FlowDes is FTHREE"
    THEN "Udamp is D11" (Credibility = 0.7)

Rule Generation using a Simple Quantitative Model

The data used to generate the rules relating the air temperatures and the fractional flows are obtained by simulating the thermal behaviour of a mixing box using a simple model based on steady-state energy and mass balance:

$$\dot{m}_1 T_f + \dot{m}_2 T_r = (\dot{m}_1 + \dot{m}_2) T_s$$

where $\dot{m}_1$ and $\dot{m}_2$ are the fresh and return air flows

and T_f , T_r and T_s are the fresh, return and supply air temperatures.

Thus,

$$T_s = r T_f + (1-r) T_r$$

where $r = \dfrac{\dot{m}_1}{(\dot{m}_1 + \dot{m}_2)}$ is the fresh air fraction

Three fuzzy sets ("low", "medium" and "high") are used to describe the fresh air temperature over the range 5° to 13°C. Three sets with similarly shaped membership functions are used to describe the return air temperature over the temperature range 18° to 26°C. Five sets are defined for supply air over the range 14° to 17°C. Six uniformly distributed sets are used to describe the fresh air fraction over the range 0.0 to 1.0.

The credibility of each rule is equal to the degree of membership of the set associated with its conclusion if the numerical values of T_s , T_f and T_r which coincide with the centre of each of the fuzzy sets (see Fig. 3) are used to calculate values of $\dot{m}_1$. Three of the rules generated in this way are shown below :

IF "Toutdoor is LOW" AND
        "Treturn is LOW" AND
                "Tsupply is VERY_LOW"
        THEN "FlowRatio is LOW"
                (Credibility = 0.077)

IF "Toutdoor is LOW" AND
        "Treturn is LOW" AND
                "Tsupply is VERY_LOW"
        THEN "FlowRatio is LOW_MIDDLE"
                (Credibility = 0.923)

IF "Toutdoor is HIGH" AND
        "Treturn is LOW" AND
                "Tsupply is VERY_LOW"
        THEN "FlowRatio is VERY_HIGH"
                (Credibility = 1.0)

A total of eighty-three rules with non-zero credibility are generated.

Rules Derived from Expert Knowledge

The rules compensating for the presence of hysteresis and rate-limits are based on manufacturers' data [Hawkins et al 1990] :

IF "the dampers are opening"
  AND "are to continue to open"
    AND $\Delta Uc \leq R$ THEN $\Delta Ua = \Delta Uc$

IF "the dampers are closing"
  AND "are to continue to close"
    AND $| \Delta Uc | \leq R$ THEN $\Delta Ua = \Delta Uc$

IF "the dampers are closing"
  AND "are now to begin opening"
    AND $\Delta Uc \leq R - H$ THEN $\Delta Ua = \Delta Uc + H$

IF "the dampers are opening"
  AND "are now to begin closing"
    AND $| \Delta Uc | \leq R - H$ THEN $\Delta Ua = \Delta Uc - H$

ELSE $\Delta Ua = \Delta Uc = 0.0$

where R is the maximum movement that the actuator can make in one sample time
H is the magnitude of hysteresis
Ua is the position of the actuator
Uc is the desired position of damper blades

and it is assumed that $R > H$

Expert knowledge is also employed when deriving rules that cover extreme conditions, such as for zero desired flow through the dampers, since leakage through the fully closed dampers can be significant. Rules must also be included to define the relationship between the exhaust flow and the fresh air flow, and to govern the minimum amount of fresh air flow. For example,

IF "the pressure in the building is close to atmospheric"
THEN Desired exhaust flow = Desired fresh air flow

IF "Desired fresh air flow is too small"
THEN Desired fresh air flow = Minimum flow
AND Return air flow = Desired supply flow - Fresh air flow

Expert rules must also be included to compensate for the temperature rise across the supply fan.

Simulation of the Air-handling Unit

The performance of the controller is assessed using a building emulator [Haves et al, 1991] which simulates the dynamic operation of an air-handling unit. The rule-based controller is implemented in a prototype version of the outstation of a new type of building energy management system which, in addition to the usual general-purpose microprocessor, has a fuzzy co-processor that serves as the inference engine for the rule-based controller.

The simulated air-handler has a mixing-box consisting of three identical sets of multi-vane, opposed-blade, dampers. The resistances of the inlet and outlet grilles and the duct work in the fresh and exhaust air sections are modelled separately, as is the resistance in the section of duct containing the return air dampers. The extract air flow-rate is equal to the supply air flow-rate at all times. The model of the dampers is identical to that used in the calibration tests. The authorities of the inlet, exhaust and return dampers (0.08, 0.08 and 0.7 respectively) are typical of those found in real plant [Harrold and Gait 1981]. Ideal measurement of the pressure drops across each set of dampers is assumed. The damper actuators take 100 seconds to move from fully-open to fully-closed, and the linkages introduce negligible hysteresis. The return air temperature is treated as an independently controlled boundary condition. The heating and coiling coils are modelled but are turned off throughout the experiments. All temperature sensors have a time constant of 30 seconds.

Performance of the Controller

Figure 4 shows the desired supply temperature, the temperature of the air immediately after it leaves the mixing-box and the temperature of the air supplied by the air-handling unit. The outside temperature is held constant at 9°C and the return temperature at 22°C, so that the temperature difference seen by the mixing-box is relatively large. Good control of the mixed air temperature is observed throughout the operating range. The steady-state accuracy of the supply air temperature is satisfactory, although the large thermal mass introduced by the coils, when they are turned off, does result in a sluggish transient response. The controller is seen to respond equally well to both small and large changes in set-point. As can be seen in Fig. 5, the fresh air flow is very close to its desired value at all times, and the supply air flow-rate remains relatively constant, despite the significant changes in the fresh air flow.

The results shown in Fig. 6 demonstrate the controller's ability to follow set-point changes when there is a smaller 9°C temperature difference between the outside temperature and the return air temperature, which is held constant at 18°C. As before, the response to both small and large changes in set-point is accurate and well damped.

The response of the flow controllers to disturbances resulting from fluctuations in fan speed is shown in Fig. 7. The desired supply air temperature and desired supply flow-rate are held constant at 13.5°C and 1450 l/s, respectively. The fan-speed is ramped between 80% and 90% of its nominal speed. There is relatively little change in the steady-state value of either the supply air temperature or the fresh air flow even though the differential pressure across the dampers varies from about 50 Pa to 130 Pa. The supply air temperature and fresh air flow-rate are normalised to their desired values; the differential pressure across the dampers is normalised to its maximum value.

Conclusions

For control purposes, the behaviour of highly non-linear plant can be adequately described by combining a relatively small number of fuzzy rules generated from simulation data with Boolean and fuzzy rules based on expert knowledge. The method of generating the rules requires only modest computing power and relies on realistic simulation of only the basic features of the behaviour of the plant. Generation of rules from experimental data obtained by factory calibration of plant is also possible.

The use of a receding horizon control strategy allows design of a rule-based controller for a mixing-box which works well over a wide range of operating conditions and is suitable for dedicated implementation in packaged controls. Practical methods of measuring the differential pressure across the dampers, including the possible use of low cost dynamic pressure sensors, are now being examined.

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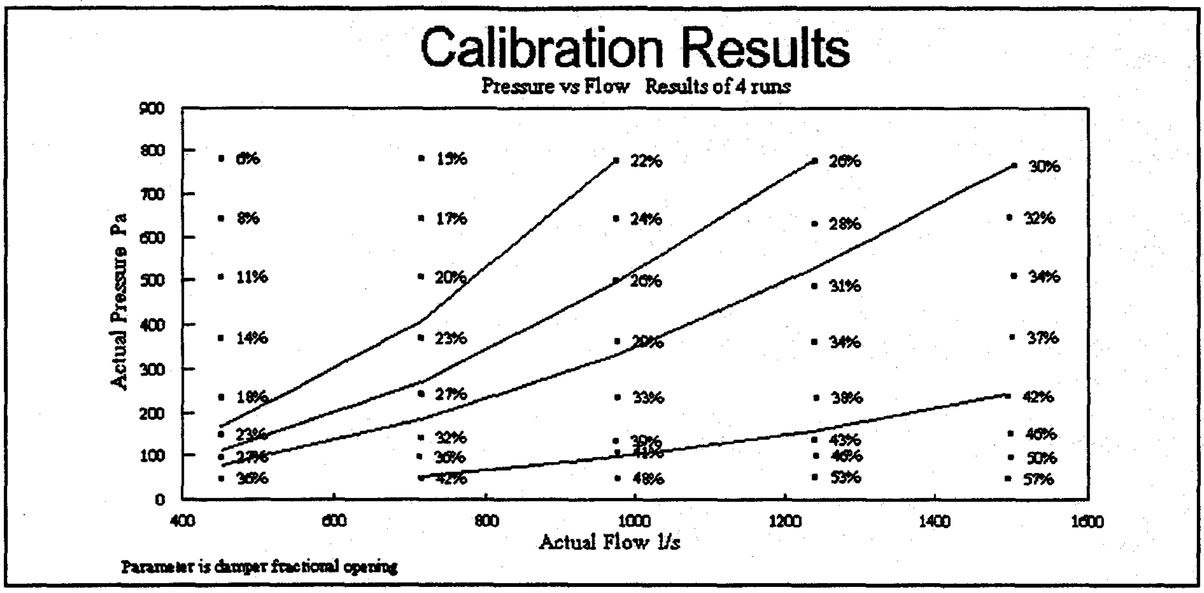

Figure 1 Damper calibration data

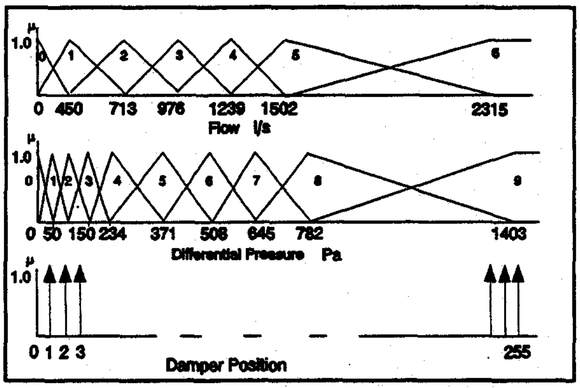

Figure 2 Fuzzy sets used to describe flow, differential pressure and damper position

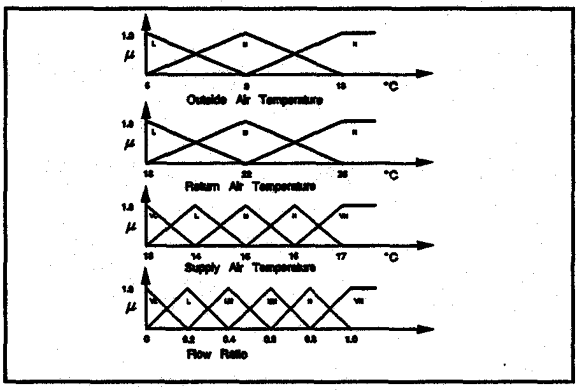

Figure 3 Fuzzy sets used to describe the temperatures

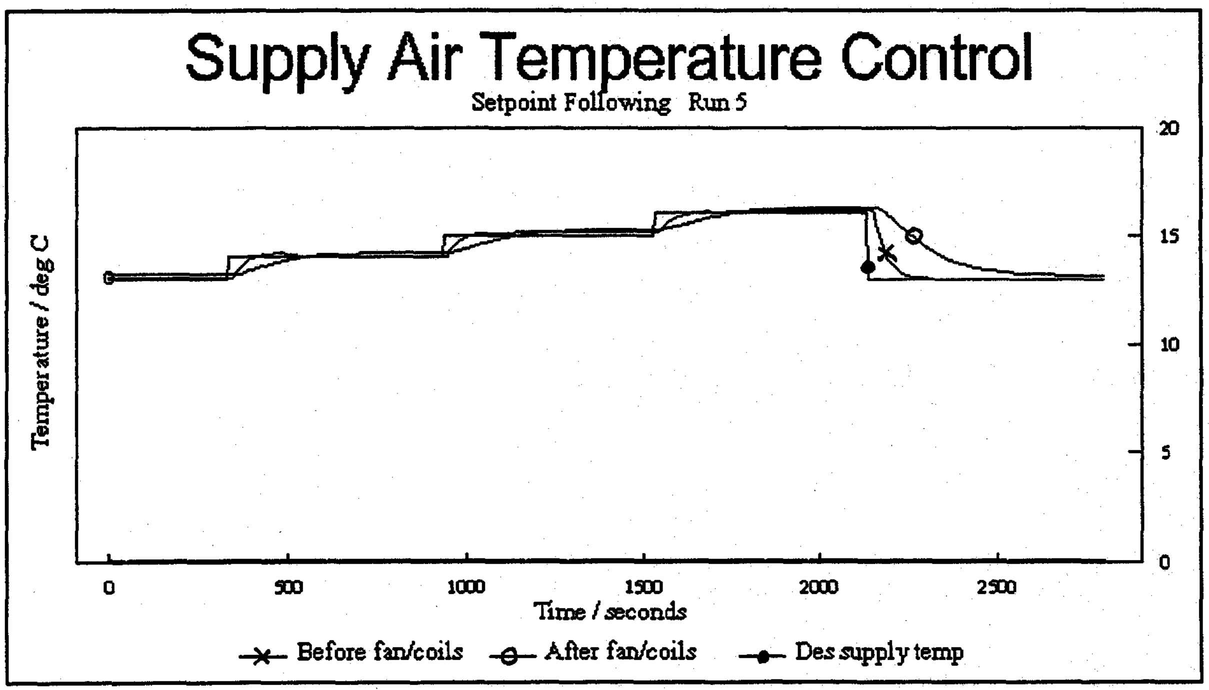

Figure 4 Supply air temperature control with a large temperature difference

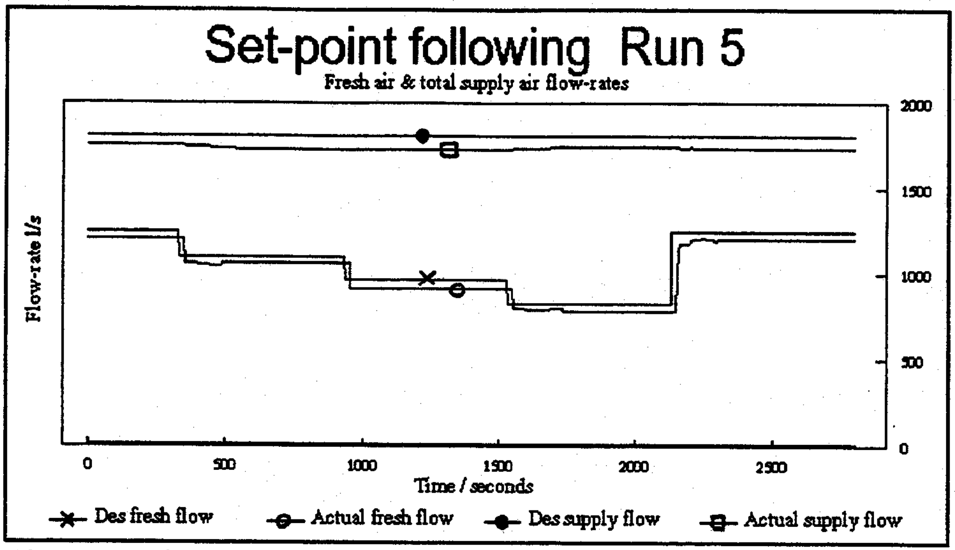

Figure 5 Flow control

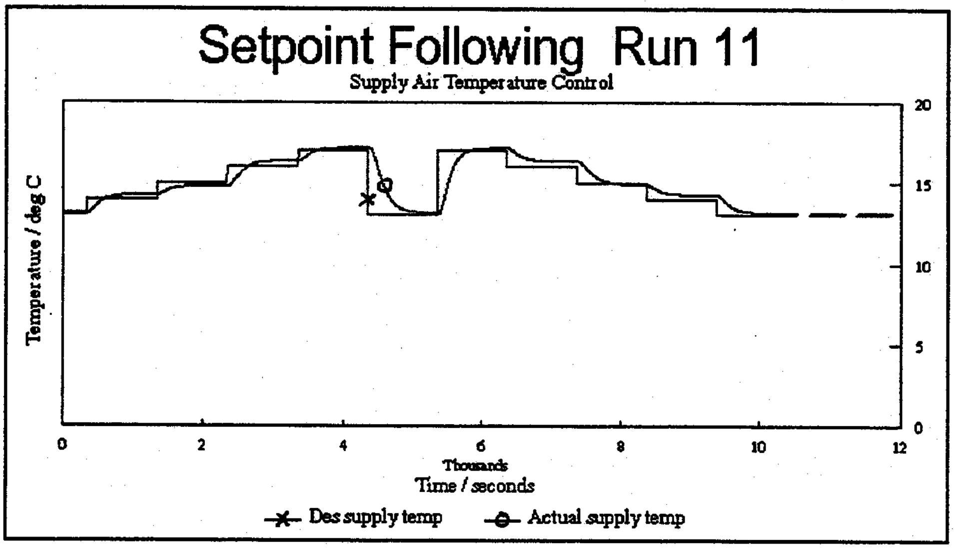

Figure 6 Supply air temperature control with a small temperature difference

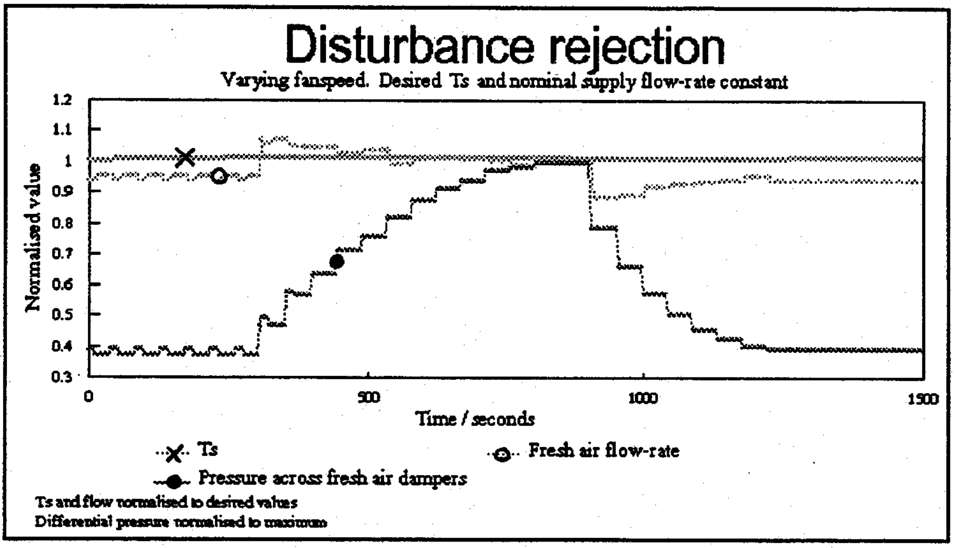

Figure 7 Flow and temperature regulation during a change in fan speed