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ANALYSIS OF DUCT SYSTEMS FOR VARIABLE VENTILATION FLOW RATES

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SYNOPSIS

Ventilation systems using variable airflow are useful in urban areas. Due to outdoor pollution and the indoor load from pollution or thermal sources, it is important to vary the airflow. This must be done without disturbing the control of the total distribution. To analyse such problems, there is need for a design aid. This paper presents a first version of a modular simulation program working in the IDA environment. The program is based on a set of individual component-models in the NMF (Neutral Model Format) language. To illustrate the usefulness, a first series of simulations of a supply air system with the main characteristics of a real office building, using two different control strategies is presented. To compare the control strategies, a test sequence of changes in the heat load of the rooms is created. Using this test sequence, it is possible to detect a difference in performance of the control systems regarding stability, ability to maintain a constant value, and ability to avoid interaction between separate controllers at different parts of the duct system.

1. INTRODUCTION

Ventilation systems using variable airflow are useful in urban areas, since it is important to minimise the flow of polluted air into the building and to vary the airflow due to the indoor load from pollution or thermal sources. One of the most difficult tasks in the design of variable air volume (VAV) systems is to vary the airflow to individual rooms without disturbing the control of the total distribution; components like dampers must work well together with the rest of the ductwork also in transient flow states. Duct systems for variable ventilation flow rates contain a large number of closed-loop controls with more or less close interaction. The controls can be divided into two main groups: those controlling the air handling unit and those controlling the supply of air throughout the building. Most of the studies in this area deal either with the dynamic performance of a single air-handling unit or with demand controlled ventilation. However, some interesting examples of studies of interaction between different parts of the control system include Haves, P., (1994 and 1995), and ASHRAE (1997) ,where the model of the air distribution system is simplified and the purpose is to study the interaction between components in the air handling unit and the terminal units. When performing a more detailed study of air distribution, it is not possible to make large simplifications of the duct system as in the three studies mentioned. The complexity of the duct layout must remain, which implies a large number of equations to be solved simultaneously resulting in slow execution speeds. The interaction of the control-loops largely depends on the design of the duct system and the selection of terminal units. An unstable system for airflow control can sometimes be stabilised to the price of a control system of high complexity and a high cost of investment. This paper introduces a first version of a simulation aid, made to study the duct system and the interaction between the terminal units, the air handling unit (fan and dampers), and control system. The simulation aid is based on a set of individual component models written in NMF code (Sahlin, P. 1996), (Sahlin, P., Bring, A., Sowell. E.F., 1996). The simulation aid will be presented in chapter 2, and an example of simulation of a supply air duct system of a small office building together with a discussion about controllability will be presented in chapter 3 and 4. The simulation aid presented is developed to be used in further studies about design of duct systems and control systems for variable airflow with the purpose to support design of simple systems.

2. DESCRIPTION OF THE SIMULATION AID

The simulation aid that will be described can be divided in two parts: a library of individual components written in NMF code that can be used in several simulation environments, and the IDA simulation environment. In this paper I will concentrate on the library of components and just briefly discuss the simulation environment.

2.1 The library of components

The library can be divided in three parts: duct system, control system, and boundary. In this paper I will only describe the models briefly, the full NMF code will be found in a future publication. Some of the components are created specially for this application and will be treated in the text below, while others are collected from other sources

The duct system so far contains eight component models: straight duct, elbow, transition, tee (converging and dividing), damper, fan, and point of measurement. All of the components, except point of measurement, have their origin in the IDA MAE (Multizone Air Exchange) application (Bring, A., Sahlin, P., 1993). Although some changes have been done in some of them, they will not be presented here. The model Point of measurement is simply used to supply data from an arbitrary point in the duct system, to the control system without modification of the other duct components. It contains no equations or parameters. The model consists of four links that can be connected to the transducers below and two links for letting the air pass by.

The control system so far contains eight component models, actuator/motor, transducers (temperature, pressure, flow, and X-transducers), PI-controller, and two models used to compare and select max or min value of a number of signals. The motor or actuator has constant speed. The actuator starts moving when the difference between current out signal (damper position) and in signal from the controller exceed specified limits and stops when the difference falls below other limits. To describe the actuator, values of the dead bands, the normalised inverted speed, and the minimum actuator position must be supplied. If the dead band is set too large it makes the system harder to control, and if it is to small the simulations will be harder to perform due to numerical problems. All the transducers used (temperature, pressure, flow, and X) are based on the same structure. The out signal is between 0 and 1. The lumped capacitance method is used and simplified to a single time constant. To describe the model the values of the time constant, and maximum measured value allowed must be supplied. The X transducer is used for the measurement of moisture or any pollutant in the air. The model of the PI-controller is a classic one with anti wind-up and the out signal limited to a value between 0 and 1. The tuning of the controllers is crucial for the behaviour of the simulated system. The models, findmax and findmin are used to select maximum or minimum value of a varying number of in signals and send the value to the control unit. The component must be connected to at least three signals. There are no parameters to supply.

The boundary so far consists of one model of a room – and a simple model – outside air properties, used as an air intake. The room model serves as a boundary for the duct system. The thermal performance of the room is modelled by the use of the lumped capacitance method for simulating the wall temperatures. The air is modelled as perfectly mixed, and in this model the exhausted air always equals the supplied. The model, outside air properties, contain no equations, only parameters used to set the outside pressure, temperature, and pollution. When no air-handling unit is available, these values are used to set the values of the treated air.

2.2 The IDA simulation environment

The IDA simulation environment consists of three separate parts: NMF-translator, IDA-modeller, and IDA-solver. They are all needed when creating an application, but when it is finished you only use the IDA-modeller and -solver. The NMF - translator is used to create Fortran files from NMF models to be used by the IDA solver or other simulation platforms such as TRNSYS and HVACSIM+. The NMF-translator is also used to create files that can be used together with the IDA modeller. IDA- modeller is the graphical interface, which helps to put individual components together into larger systems. (Sahlin, P., 1993). From this platform you create your system model and perform all simulations, it also supplies the possibility to create scenarios for the simulation by using text files or tables. It is also possible to log any variable to an arbitrary number of output files. It is possible to use a toolbox in the modeller to create tailored applications. The most important part of the environment is the IDA - solver, the variable step length solver of systems of differential and algebraic equations (Sahlin, P., Bring, A., 1991).

3. SIMULATIONS OF AN OFFICE BUILDING

3.1 The simulated duct system

To illustrate what kind of problems that can be studied with the simulation aid, simulations of a simplified model of the duct system of an existing office building have been performed. The building has two floors, each with 6 rooms. In the real building, the air is supplied to the office rooms by VAV terminals and exhausted through CAV (Constant Air Volume) dampers in the sanitary areas and VAV dampers in the corridor. The air handling units are located at the top floor and each unit supplies 15 m^3/s air at a pressure of about 1600 Pa. From each unit the air is distributed through three main ducts, located at the south, central, and northern parts of the building. The air temperatures are equal for all mains and kept constant at 15 degrees. The initial strategy is to control the fan rather slowly, the dampers in the branches fast and the VAV Terminal units quite slowly. The variable speed control of the fan is set to maintain a constant pressure of 350 Pa at the top of the main ducts. There is one pressure transducer at the top of each main, figure 1, the pressures are compared and the lowest one selected to control the system. At the beginning of each horizontal branch there is a damper for maintaining a constant pressure of 200 Pa at the end of the branch. These dampers have linear characteristics and fast actuators. The room temperature is maintained constant at 20 degrees by separate dampers in each room. In this small study, only the supply system was simulated.

One difficult part of the design is to tune the control system. A modified Ziegler-Nichols method (Sørensen, B.R., Novakovic, V., 1996) was used as a first estimation and after that corrections of the gain and integration time were made. The integration time was set to a number close to the inverted speed of the actuator and the gain was set to the best value of a few tested by simulation. Each time the pressure of the dampers was changed, tuning of the controllers, and start up calculation had to be performed, which was very time consuming.

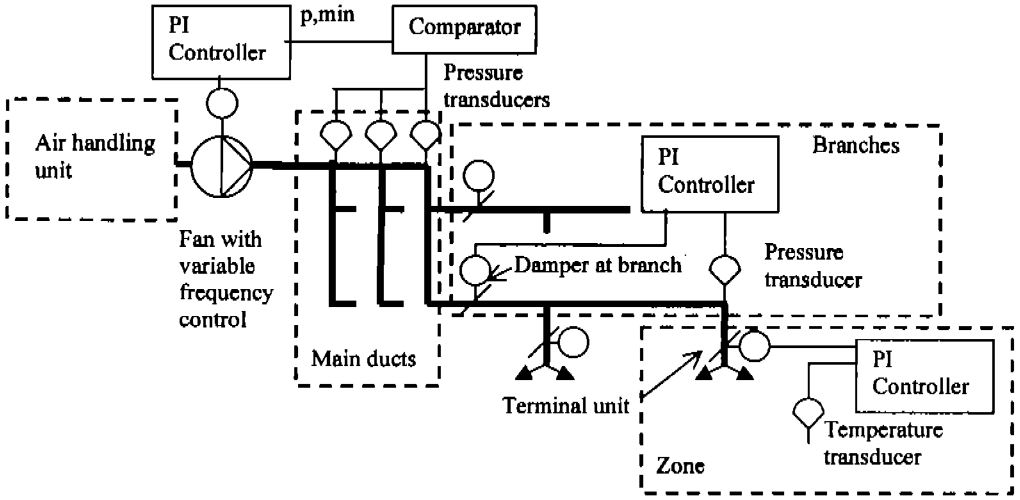

Figure 1: Scheme of the control system.

The duct system was designed to meet the load of 150 W of equipment, 80 W lightning, and 1 person. The dampers of the branches were designed to a pressure drop of about 150 Pa (40 % open) and the terminal units to a pressure drop of 200 Pa (55 % open).

3.2 Simulated scenarios

A question that often is raised is; what are the characteristics of a good controlsystem? An easy way to make an evaluation is to integrate the error in some way, usually its squared or absolute value (Schmidtbauer, B., 1988). It is not only the error that is important, usually one wants to minimise the signals from the controllers to avoid unnecessary movements of the dampers (Glad, T., Ljung, L., 1997). According to ASHRAE 825-RP (ASHRAE, 1996) you can look at two levels, first at one single loop and then at the entire building. In the first case, the common criteria of good control, static accuracy, rise time and stability can be used. If you look at the entire building, it becomes more complex. There are often compromises to be made among contradictory conditions. Among the factors you can select, such as criteria of good control, are discomfort, energy use, maintenance, and investment. There are also more factors to be considered as noise level and disturbing frequencies generated by modulation of dampers and the fan speed. A measure that includes several of the factors mentioned could be to perform a simulation of a sequence of relevant changes in the load of the rooms and measure the time at which the controlled quantity is stable and within its wanted limits. This is illustrated in figure 2. The controlled variables of a VAV system are usually the room temperature or the pressure at some point in the duct system. By summarising the time ranges t1, t2… that correspond to periods of stability and accuracy, and dividing the sum by the total time, you reach a figure that approaches one when the control is perfect. There will always be some fluctuations in the system. This implies that a system must be considered as stable when the fluctuations of the variables are within a specified limit. The accuracy is also defined, as a limit within which the variable should stay. When looking at the fluctuation of the pressure of the terminal units, if the limits are expressed as a fraction of the nominal pressure loss of the dampers, the change in supplied mass flow during the fluctuations will be the same, not depending of the actual nominal pressure loss. A fast and stable control should give a high figure. A high figure could also imply low wear of the equipment and small risk of unwanted disturbing frequencies.

The simulations were started at a steady state condition and the changes of the heat load in the rooms were then applied to the system. The duct system was designed for 70% of the maximum load used in the sequence. Besides the original control, one simplified control strategy with the pressure control of the branches removed was tested.

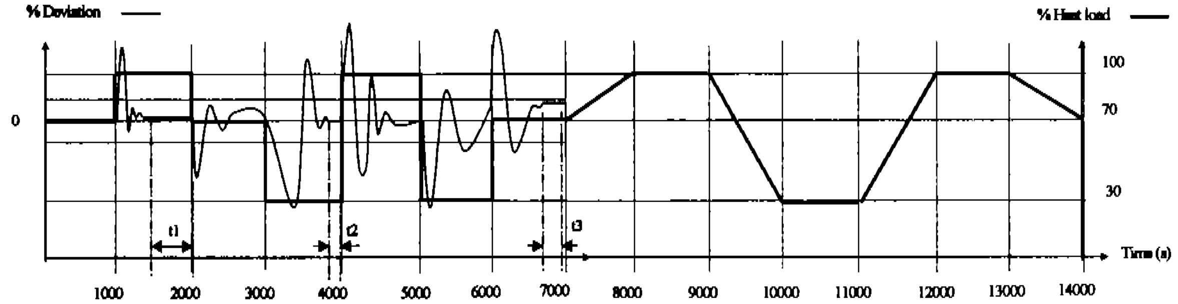

Figure 2: Sequence of heat load and a fictitious example of a deviation of one controlled variable.

For each of the two control strategies, five simulations were performed each, using the nominal pressure over the dampers as presented in table 1. For one set of pressure, simulations were performed using different gain (k) of the controllers of the terminal units.

Table 1: Summary of the scenarios simulated.

	Scenario, pressure in branch and terminal unit				
Damper in branch	150	300	50	50	150
Terminal unit	200, k=20	50, k=5	300, k=20	300, k=5	25, k=5

3.3 Performing simulations

When using the IDA simulation environment such a duct system is quite easy to model. Looking at the graphic interface of IDA Modeller, it is easy to follow the structure of the model (see figure 3). The simulations are controlled by supply of data through input files. The parameters of the individual components can be changed by the use of a dialog box that appears when the symbols are opened. Before any changes in load are put to the system it has to be in a steady state. It usually takes long simulation runs to create a steady state starting condition, but it is possible to make one start up calculation that can be used as a starting condition for all simulations.

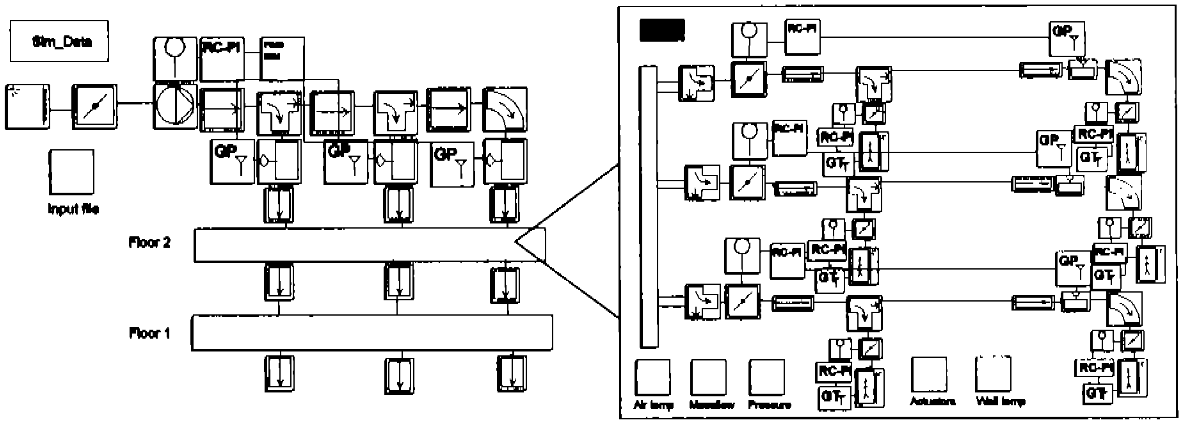

Figure 3: The model of the building as it looks in IDA Modeller. When one floor is opened the duct system appear.

4. RESULTS

Table 2 shows the scenarios simulated, the first scenario is presented in more detail. Figure 4 shows what happens to the temperatures of the rooms when the sequence, figure 2, is used for one room at each floor. As you can see, there is no problem to keep the room temperature within rather strict limits, but this does not say much about the movements of the dampers and changes in fan speed. Figure 5 shows the pressure before the terminal units: This figure more clearly shows the dynamics of the system. The control has a problem to maintain a constant pressure of 200 Pa. It is also possible to detect some interaction between the different controls.

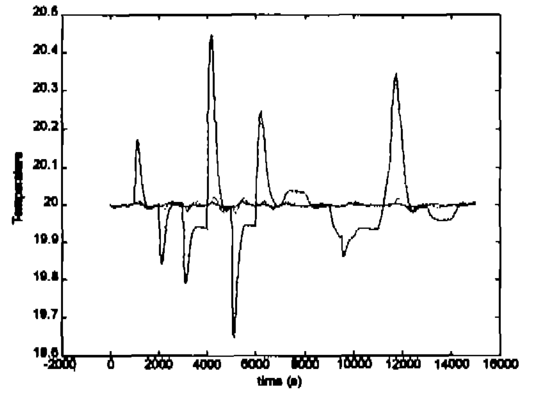

Figure 4: Temperatures of the rooms when using the test sequence of one room at each floor.

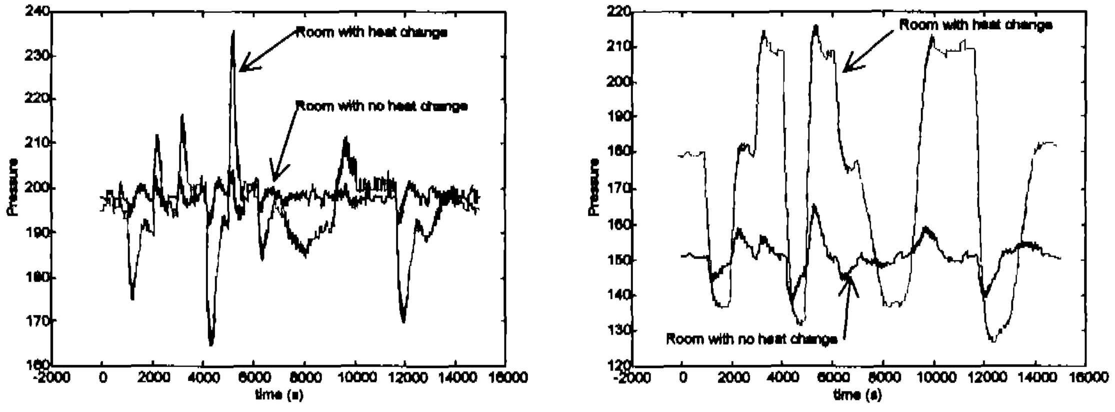

Figure 5: Pressure before the room dampers, original control and simple control respectively.

Figure 4 and 5 show the result, with 150 Pa pressure loss over the damper in the branch, and 200 Pa pressure loss at the terminal unit. A calculation was performed of the ratio described in chapter 3.2, with the limit set to 10%, and with the assumption that the system is stable if the oscillation is below 1%. The result when looking at the pressure before the terminal unit of the room with changes of heat load become 0.29 for the original system and 0.44 for the simplified system, and in a branch where no changes take place the result become 0.75 and 0.32 respectively. When looking at the simplified system, and analysing the pressure before the room with the changes, it is not possible to use the limit of 10%, since the pressure loss in this system should vary when the flow increases. It can also be seen from the simulations that there is almost no difference in the behaviour of the fans in the two simulated systems. A summary of the result is presented in table 2. When looking at the mean values of the two ratios for each control algorithm the best performance for the original control is obtained at scenario 4, and for the simplified control at scenario 3. Least interaction between controllers at different branches is obtained for the original control at scenario 2, and the most stable pressure is obtained for the simplified control at scenario 2.

Table 2: Summary of the performance ratios for the systems simulated.

	Scenario, pressure in branch and terminal unit				
	1	2	3	4	5
Pressure at damper in branch	150	300	50	50	150
Pressure at terminal unit	200,k=20	50, k=5	300,k=20	300, k=5	25, k=5
	Performance ratio, pressure loss of terminal units				
Original control, heat change	0.29	0.13	0.29	**0.645**	0.05
Original control, no heat change	0.75	**0.88**	0.44	0.77	0.46
Mean value:	*0.52*	*0.505*	*0.365*	***0.705***	*0.255*
Simple control, heat change	0.44	0.09	**0.53**	0.284	0.04
Simple control, no heat change	0.32	0.75	0.683	**0.77**	0.52
Mean value:	*0.38*	*0.42*	***0.605***	*0.525*	*0.28*

5. DISCUSSION

There is still a lot of work remaining until the tool presented can be used by engineers in the daily work, but the examples in this study show its usefulness. One of the advantages of this tool is the possibility for the user to select which aspects to study; any variable can be logged to a file during the simulations, and any variable can be kept constant. The simulation time for systems like those presented is about an hour for a 266 MHz computer, but the developments of the computers will shorten this time in a near future. The tool still lacks some important models such as discrete controllers, and more advanced room models that support multiple supply and exhaust terminals and leakage to other rooms and to the environment.

As discussed in chapter 3.2, the definition of good control depends on what system of the building that is studied. The duct system is something in between the entire building and a single control-loop. For this, a test sequence of the kind presented here seems appropriate. When calculating performance ratios for different control strategies and scenarios, the values obtained are in such a wide range that it is possible to detect differences between the systems. If the compared systems behave slowly, the time between the changes in load must be increased if it should be possible to detect the difference between them. The evaluation of the test sequence was performed manually, but a model for estimation of such control deviation will be added to the next version of the library of components.

When looking at the overall performance by using the sum of performance ratios, it looks like the original control with most of the pressure loss located at the terminal unit and a moderate gain at the controller produces the best result. Least interaction between controllers located at different branches seems to be obtained when using the original control with most of the pressure loss located at the damper at the branch. Also, as when looking at the best overall performance, moderate gain. Although this study is based on too few simulated scenarios, it is evident that the behaviour of the duct system is determined by distribution of the pressure loss throughout the system. As could be expected, the interaction between controls at different branches depends largely on the pressure loss at the damper located at the branch. At a constant sum of the pressure loss at the branch and terminal unit there probably exists a combination that gives the highest performance ratio when looking both at an individual controller and at the distribution of disturbances throughout the duct system. Also the tuning of the controllers plays an important role. To change the gain of the controllers will often have the same effect as changing the nominal pressure loss of the dampers.

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