FAULT MODELLING IN COMPONENT-BASED HVAC SIMULATION

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ABSTRACT

Models of faulty components or processes may either be used on-line as part of a fault detection and diagnosis (FDD) system or may be used in simulations to train or test FDD procedures. Some faults may be modelled by choosing suitable values of the parameters of fault free models, whereas other faults require specific extensions to fault free models. An example of the modelling of various faults in a cooling coil subsystem is presented and different methods of using simulation in testing and training are discussed.

INTRODUCTION

There is growing interest in the development of fault detection and diagnosis (FDD) methods for buildings and HVAC systems. Modelling and simulation can be used in the development of FDD methods in three main ways:

- on-line models can be used as part of the FDD procedure;
- simulations of faulty systems can be used to train on-line 'black box' (empirical) models used in FDD systems;
- simulations of faulty systems can be used to test FDD methods.

The on-line models used in FDD procedures can be either analytical, first principles, models or empirical, 'black box' models, depending on the FDD method. The first principles models are generally simplified versions of the models used in training 'black box' models and in testing various types of FDD methods. Model-based FDD methods typically operate at the subsystem level and use either a single model or a small group of models connected together.

At present, FDD methods for HVAC systems do not involve on-line simulation at the system level and hence the problems of connecting models and efficiently solving the resulting equations do not arise, although they may well do so in the future as FDD methods are developed further. These, and other, problems do arise in the use of simulation to train and test FDD methods. One particular problem is that a number of the forms of ideal behaviour assumed in most simulation programs break down in the presence of faults in the HVAC system. Detailed modeling of all parts of the system that interact with the part of the system being studied is therefore required. At present, the only practical method of achieving the required level of detail is the use of a component-based simulation program such as TRNSYS [1], HVACSIM+ [2], IDA [3] or SPARK [4, 5].

A set of component models for HVACSIM+ and TRNSYS that treat the performance of secondary HVAC systems, including VAV systems, has recently been produced for the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) [6]. The models are specifically designed to support the evaluation of control algorithms and strategies and to be easily extended to treat faulty operation. This work provides the foundation for much of what is described in this paper.

Section 2 reviews different approaches to fault detection and diagnosis in buildings, concentrating on model-based approaches. Section 3 describes and categorises some of the faults that occur in secondary HVAC systems and discusses various difficulties in characterising quantitatively their behaviour. Section 4 is a discussion of ways in which faults may be treated in component models, illustrated with an example. Section 5 describes the use of simulation in the development and testing of FDD methods.

FDD IN BUILDINGS

Approaches to FDD

Any fault detection procedure must incorporate knowledge about the behaviour of the relevant process. Fault diagnosis procedures must also incorporate knowledge about the behaviour of the process in the presence of the faults that are of interest. Two widely used means of representing this prior knowledge are knowledge bases (e.g. expert rules) and quantitative models. Quantitative models may be divided into two categories:

- first principles models, i.e. models based on a scientific analysis of the process;
- empirical or 'black box' models, e.g. artificial neural networks.

In first principles models, the generic information about the process is embodied in the equations; the parameters that appear in the equations are used just to particularise the model so that it represents one particular item of equipment. The equations in 'black box' models are intended to be general enough to model, within limits, any type of behaviour. All the information about the process, generic and well as specific, is embodied in the parameters. However, the distinction between the two types of model is not clear cut, since most first principles models contain some empirical relationships and black box models incorporate implicit prior knowledge of the process in the choice of their inputs and outputs. The key distinction between the two types of models, in the context of FDD, is that first principles models have physically meaningful parameters that can, if necessary, be determined from design information and manufacturers' data, whereas the parameters of empirical models. e.g. the weights in artificial neural networks, must be determined by training using measured or simulated performance data.

The process of fault *detection* only requires knowledge of the behaviour of the correctly operating process. Most fault detection methods involve the comparison of the actual behaviour of the process with a prediction of the expected behaviour of the process in the absence of faults. A significant difference, an 'innovation', indicates the presence of a fault but does not, of itself, indicate the nature of the fault. By contrast, the process of fault *diagnosis* requires information about the behaviour of the system in the presence of the different faults that may occur. Three approaches to fault diagnosis involve:

1. Analysis of how the innovations vary with operating point
2. Comparison of the actual behaviour with the predictions of different fault models
3. Estimation of the parameters of an on-line model that has been extended to treat particular faults.

One method of implementing the first approach is to use a rule-based system [7]. The rules can be obtained from experts and then checked for consistency, completeness and correct implementation by testing using simulation, or the rules can be generated using simulation. If black box models are used in the second approach, simulation may be the only way to generate training data, since it is not usually possible to obtain training data from real, faulty, systems. The extended online models used in the third approach are often simplified versions of the component models used in the simulation of faulty systems [8].

Model-Based FDD in Buildings

Two main approaches to model-based FDD in buildings may be discerned at the present time:

- whole building energy simulation ('energy monitoring and targeting')

- component-level FDD

The models used in energy monitoring and targeting are often very simple, e.g. models based on degree-days, although both detailed analytical models, such as DOE-2, and black box models, e.g. artificial neural networks, are being investigated for this application [9, 10]. In most cases, these models are configured to represent correct operation, so that, on their own, they only detect faults; further analysis is required to produce a fault diagnosis.

Component-level, model-based, FDD involves the use of on-line models of individual items of equipment, e.g. fans, coils, and is only really practical as an extension to a computer-based control system. Again, these models may either be analytical, first principles, models or empirical models [11, 7].

In general, on-line models are simplified models, usually for reasons of computational efficiency and ease of configuration. The use of simulation to train on-line models and to test FDD methods requires the use of more detailed models. Two important requirements for such models are that they:

- treat the required types of faults
- correctly treat fault-free operation over a wider operating range than is normally encountered

The first requirement is obvious; the main problems are to determine which faults are important and to determine how they should be modelled. The second requirement is less obvious; a fault in a particular component may shift the whole system to an operating point that is never encountered during the fault-free operation of a correctly designed system. A particular problem is that empirical models based on curve fitting, e.g. fan models, are likely to produce highly erroneous results outside the range over which the curve fit was performed. Models based on first principles are less susceptible to such problems, but may still produce inaccurate results when the model operates at conditions under which assumptions or approximations made in the model are no longer valid.

FAULTS IN HVAC SECONDARY SYSTEMS

Surveys of faults in HVAC systems have been performed as part of the International Energy Agency's Annexe 25 [12]. The faults that were found can be categorised as:

- design faults
- installation faults
- abrupt faults
- degradation faults

Design faults and installation faults should ideally be detected before the building becomes operational but, in practice, often remain undetected because of poor commissioning. Abrupt faults are usually detected immediately if they have a major effect on the operation of the system. However, some abrupt faults, e.g. the failure of the return fan in an air handling unit, may have an effect that, while significant, falls short of being catastrophic. Degradation faults are difficult to detect in their early stages, but there is considerable interest in detecting such faults before they have a serious effect on the performance of the system. Table 1 lists examples of faults that occur in secondary HVAC systems, together with their symptoms.

Faults may either be described by their effect on the performance of the component in which they occur or by their physical nature. In either case, the description may either be qualitative or may fail to define quantitatively the performance of the component except at a particular operating point. For example, 'control valve with 2 % leakage' defines the performance of the valve when it is fully closed but does not specify how the characteristic is modified at other stem positions, e.g. when the valve is nearly, but not fully, closed. The modification to the characteristic is likely to depend on the physical cause; the effect of erosion of the valve seat is likely to be different to that of foreign material in the valve chamber that restricts the movement of the valve stem. There is an almost complete absence of comprehensive measurements of the effect of individual faults on the performance of HVAC equipment. This absence limits the fidelity with which certain types of fault

Table 1: Examples of faults and their symptoms

Category	Physical Cause	Symptoms
Design	Undersized fan, coil etc	Reduced capacity
	Oversized control valve or damper	Non-linear subsystem response
	Intake and exhaust louvres too close	High mixed air temperature, poor IAQ
Installation	Controller gain too high	Oscillation, excessive wear
	Cooling coil connected for parallel flow	Reduced cooling capacity
	Actuator linkage hysteresis	Poor control (limit cycle)
	Valve ports connected incorrectly	Non-linear subsystem reponse
Abrupt	Broken drive belt (fan/pump)	Reduced/zero flow rate
	Seized actuator	Loss of control
Degradation	Blocked filter	Reduced flow rate and/or increased energy consumption
	Slipping fan belt	Reduced air flow rate
	Coil fouling	Reduced heating/cooling capacity
	Sensor drift	Set-point not attained
	Leaking valve/damper	Increased energy consumption

may be modelled.

FAULT MODELLING

Faults may be modelled in two different ways, depending on the nature of the fault and how detailed the model of fault-free operation is:

- changing parameter values in a fault-free model: for example, coil fouling may be treated in a simple coil model by reducing the UA value;
- extending the structure of the model to treat the fault(s) explicitly: for each fault, a parameter may then be introduced that defines the degree or extent of the fault, e.g. in a detailed coil model, fouling may be defined by a parameter that specifies the thermal resistance of the deposits.

Examples of faults that can be modelled without extending the fault-free model include:

- incorrect sizing (coils, fans, valves etc);
- defective building envelope (missing insulation, high infiltration);
- blocked filter;
- incorrect max/min flow settings on VAV box;
- coil fouling (simple model).

Examples of faults that require an extension of the fault-free model include:

- cooling coil parallel flow operation;
- coil fouling (detailed model);
- actuator hysteresis;
- mixing box short-circuiting;
- leaking valves/dampers;
- incorrect porting of 3 port valves.

If a fault is such that a basic assumption of the model, e.g. perfect mixing, is no longer justified, a major increase in the modelling detail is required. Examples include:

- poor sensor placement in ducts (incompletely mixed duct air flows);
- poor room air distribution (imperfectly mixed room air);
- loss of refrigerant charge.

Example – Cooling Coil and Valve

Figure 1 shows a cooling coil and its associated three port control valve. The duty is controlled by varying the water flow rate through the coil. As the demand for cooling increases, the position of the valve stem is changed so that the resistance of the flow port decreases and the resistance of the bypass port increases. If the flow port has an exponential (equal percentage) characteristic, the bypass port has a linear characteristic and the valve is correctly sized, the flow rate through the common port will be approximately constant and the relationship between the valve position and the duty will be approximately linear.

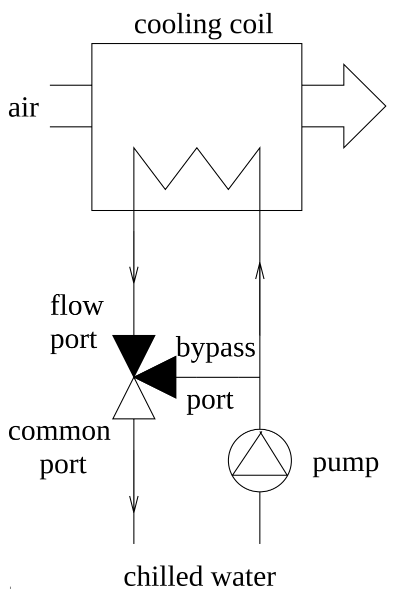

Figure 1: Cooling coil and three port control valve

Figure 2 shows the results of modelling various faults in a cooling coil configured as shown in Figure 1. The faults are:

- reversed chilled water connections to the coil, resulting in parallel rather than counter flow;
- tubes fouled by 1 mm of calcium carbonate
- control valve connected incorrectly:
  - flow and by-pass transposed
  - common and by-pass transposed

The coil and valve sizing parameters are derived from an air handling unit in a real building [6]. The control valve has an authority of 0.5 and a rangability of 35:1.

The left hand plot shows the fractional water flow rate through the coil as a function of valve stem position. The fault free case, the parallel flow case and the fouled case all have the same flow rate (only the thermal effects of coil fouling have been treated). The case with the flow and by-pass connections transposed exhibits the installed characteristic of a linear valve with an authority of 0.5. The case with the common and by-pass connections transposed has the by-pass valve port in the primary circuit. When the flow port is fully open (valve position = 1), the by-pass port is fully closed, resulting in zero primary flow rate and hence zero flow rate through the coil. The flow rate is also reduced at intermediate valve stem positions, since the flow and by-pass ports are effectively in series.

The right hand plot shows the resulting coil duty, expressed as the air side approach:

$$\alpha_a = \frac{t_{ao} - t_{ai}}{t_{wi} - t_{ai}}$$

where t_{ao} is the air outlet temperature, t_{ai} is the air inlet temperature and t_{wi} is the water inlet temperature.

The cases of parallel flow and 1 mm of tube fouling both show a moderate but significant reduction in duty. The case with the flow and by-pass connections transposed exhibits a more non-linear transfer characteristic, with quite high gain at low duties compared to that at high duty. This variation in gain, which can also arise from oversized control valves, is of sufficient magnitude to cause control difficulties. The supply air temperature loop must be tuned at low cooling coil duty in order to avoid unstable operation and a somewhat sluggish response will then be obtained at high duty. The case with the common and by-pass connections transposed exhibits a very abnormal

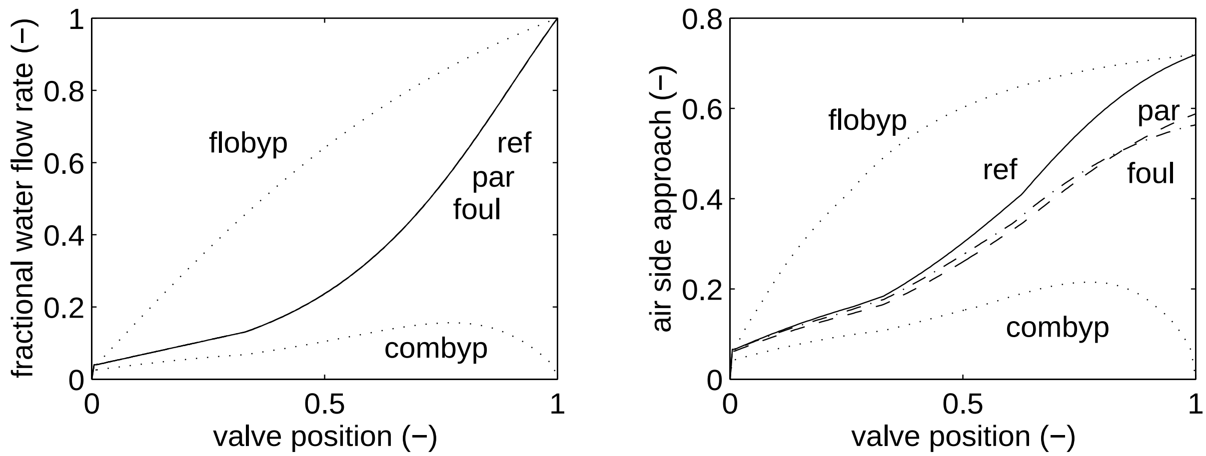

Figure 2: Cooling coil normalised water flow rates and air side approaches for correct operation (‘ref’), parallel flow (‘par’), fouled (‘foul’), swapped flow and by-pass ports (‘flobyp’) and swapped common and by-pass ports (‘combyp’)

characteristic that would produce severe performance problems. The maximum duty is very small and the negative gain at high duties will produce positive feedback, causing the control signal to saturate and the valve to remain fully open.

TESTING FDD SYSTEMS

Figure 3 shows two methods of testing FDD procedures using simulation. The configuration on the left consists of a process that simulates the HVAC system, including the controls, connected via Unix sockets to a process that implements the FDD procedure. This configuration is appropriate for use in the early stages of development when the need for flexibility and speed of execution outweighs the need for a realistic treatment of the computing environment in which the control system is implemented. A special component model is used to transfer simulation data to and from the socket, which provides interprocess communication. The component model can provide either synchronous or asynchronous communication. In the case of synchronous communication, one or both processes waits for new data to be received from the other process before continuing. In the case of asynchronous communication, neither process waits for new data and it is necessary to synchronise each process to real time in order to avoid the two processes running at different speeds. The asynchronous mode allows the two processes to run at different sampling rates, which may be more realistic.

The configuration on the right hand side of Figure 3 consists of a simulation of the mechanical equipment connected via a hardware interface to a real control system, which is also connected to an FDD system. This configuration is appropriate in the later stages of development when it is important to test the implementation of the FDD procedures in the intended computing environment, including the communication with the actual control system. The combination of simulated mechanical equipment and a real control system is sometimes referred to as an emulator [13]. It involves the use of digital to analogue converters that are driven by the simulation program and produce electrical signals that are equivalent to those produced by real sensors. The electrical signals from the control system that would normally go to real actuators are processed by analogue to digital converters coupled to the simulation and used as inputs to the actuator models.

The operation of these two configurations is described in more detail in [6]. In either case, the FDD procedures can be implemented independently of the simulation program, using a different programming language if desired, and can be modified without having to relink the simulation

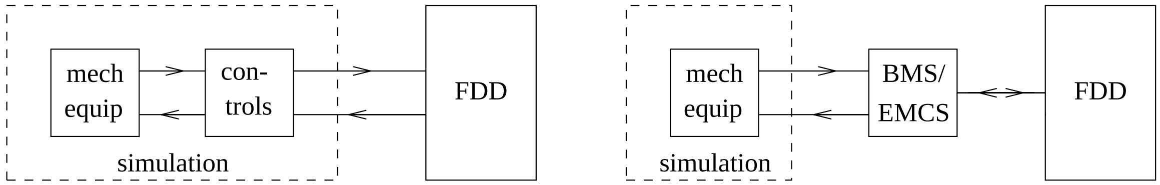

Figure 3: Methods of testing FDD procedures, left: simulated HVAC system connected to a FDD process via Unix sockets, right: simulated mechanical equipment connected to a real control system, and FDD system, via a hardware interface

program.

The bi-directional communication between the FDD system and the controller is required when the FDD procedure makes use of test signals to exercise the HVAC system under test. Test signals may be used either to check for faults directly or to generate training data for on-line models used for FDD during normal operation. Test signals are usually applied when the building is unoccupied, e.g. during commissioning. If the FDD procedure is non-intrusive, no interaction between the FDD system and the controller is required; the operating data from the HVAC system, whether simulated or real, can be stored and used off line to test different FDD procedures.

CONCLUDING REMARKS

Models of faulty components or processes may either be used on-line as part of an FDD system or may be used in simulations to train or test FDD procedures. Some faults may be modelled by choosing suitable values of the parameters of fault free models, whereas other faults require specific extensions to fault free models. An example of the modelling of various faults in a cooling coil subsystem has been presented and different methods of using simulation in testing and training have been discussed.

A general problem with fault modelling is validation of the models. There appear to be no published data sets suitable for the validation of models of faulty components in secondary HVAC systems. One particular problem is the difficulty of generating genuine faulty data, even in the laboratory. Experience in IEA Annex 25 shows that FDD researchers usually find it necessary to introduce artificial faults because waiting for real faults to occur in a particular piece of equipment is too time-consuming. However, these artificial faults often only provide a crude approximation to the effects of real faults and considerable uncertainty remains as to the detailed behaviour of components with genuine faults. This makes model development difficult and uncertain and makes validation essentially impossible at this time. A substantial and careful experimental program is required before fault modelling can progress beyond its present, semi-quantitative state.

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