A Semi-automated Commissioning Tool for VAV Air Handling Units: Functional Test Analyzer

ABSTRACT

A software tool that automates the analysis of functional tests for air-handling units is described. The tool compares the performance observed during manual tests with the performance predicted by simple models of the components under test that are configured using design information and catalog data. Significant differences between observed and expected performance indicate the presence of faults. Fault diagnosis is performed by analyzing the variation of these differences with operating point using expert rules and fuzzy inferencing.

The tool has a convenient user interface to facilitate manual entry of measurements made during a test. A graphical display compares the measured and expected performance, highlighting significant differences that indicate the presence of faults. The tool is designed to be used by commissioning providers conducting functional tests as part of either new building commissioning or retro-commissioning, as well as by building owners and operators conducting routine tests to check the performance of their HVAC systems. The paper describes the input data requirements of the tool, the software structure, the graphical interface, and summarizes the development and testing process used.

INTRODUCTION

There is a growing consensus that most buildings do not perform as well as intended and that faults in HVAC systems are widespread in commercial buildings. There is a lack of skilled people to commission buildings and commissioning is widely seen as too expensive and/or unnecessary. There is also a lack of skilled people, and procedures, to ensure that buildings continue to operate efficiently after commissioning (PECI 2004). Functional testing is a key part of the commissioning process and normally consists of a series of performance tests to make sure all the components in the system operate as intended (Sellers et al., 2003). These include start-up procedures, safety checks and performance tests at different operating points. It is not uncommon for functional testing to be planned and then not actually occur because of time or budget constraints.

One approach to these problems is to wholly or partly automate the functional performance tests procedures, using computer-based methods of fault detection and diagnosis (FDD) (Benouarets *et al.* 1994, Haves *et al.* 1996, Kelso and Wright 2005, Xu *et al.* 2005). Advantages of automation include: saving time by parallel testing, more effective use of skilled personnel, and standardized reporting. The data analysis part of the testing is relatively easy to automate, while the communication between the data analysis tool and the building energy management and control system (EMCS) is harder to automate because of the proprietary communications protocols used by most vendors, although the increasing adoption of open protocols, such as BACnet (ASHRAE 2006), is alleviating this problem. So, while the authors are pursuing fully automated functional testing as a longer term goal, the work reported here is focused on the development of a semi-automated tool ─ automated data analysis with manual data entry from the EMCS and/or temporary instrumentation. Semi-automated and automated tools each have different characteristics that are advantageous in different circumstances. Semi-automated tools can combine measurements from both permanent and temporary sensors and they avoid the need for communication with the EMCS. Fully automated tools require less effort and attention on the part of the commissioning agent and can provide a higher degree of repeatability in the test procedure. The experience gained in the use of semi-automated tools has proved useful to the authors in their on-going development of a fully automated tool.

Most active functional tests procedures emphasize start-up, safety interlocks and performance under design conditions (Sellers *et al.* 2003). The tool described here complements these other functional tests by assessing the performance of mechanical equipment over as close to the full range of operation as can be achieved with active testing over a short period of time. The use of models allows quantitative performance testing at conditions other than design conditions. Active functional test procedures have been designed to test four air-handling unit (AHU) components or subsystems: the mixing box, the heating and cooling coils, and the supply fan and return fan subsystems. The test methodology employed is described by Xu *et al.* (2005) and is similar, though not identical, to that described by Haves *et al.* (1996). The method used here uses simple mathematical models to define correct operation and detect the presence of faults. It uses expert knowledge to diagnose the nature of the faults, using fuzzy inferencing to relate linguistic rules to continuous variables such as temperature and control signal.

This paper describes the design of the tool and summarizes the test procedures and analysis methods for each component. The data needed to configure the models are discussed and the software structure, the user interface and example tests are described.

TOOL FUNCTIONAL SPECIFICATION

In new construction, the tool is designed to be used after the start-up tests and the testing and balancing (TAB) have been performed. In its present form, it tests the mechanical equipment, including the sensors and actuators, but does not test the control programing or loop tuning. It is planned to add closed loop testing of controlled performance in a subsequent development phase. The design of the tool is based on the following assumptions:

- The sensors and actuators have been connected to the field panels, though the network connecting the field panels to the operator workstation may not be installed or working. The available measurements may be from a combination of EMCS sensors and temporary instrumentation.
- Testing and Balancing (TAB) and pre-functional checks (wiring checks, stroking of actuators etc) have been performed but not necessarily completely or correctly.
- The information available to the commissioning agent includes the mechanical drawings, in particular the coil schedules and the fan information in the AHU schedule, and catalog data for the fans
- The commissioning agent may wish to enter information on all the AHU's to be tested into the tool off-site, prior to the testing

The tool is semi-automated in that the test data are entered manually and the analysis of these data is performed automatically. This has the advantages of avoiding the communication problems associated with extracting data automatically from control systems, particularly legacy systems, and allowing the test data to come partly from temporary instrumentation. Automated analysis provides a degree of repeatability and objectivity to the analysis of the data that may be helpful when communicating the existence of problems and assigning responsibility for fixing them. When using the semi-automated tool described here, it is the responsibility of the person conducting the test to identify when the system has attained an adequate approximation to steady state after each step. (Further information on the determination of steady state conditions is given in the part of the Functional Testing section dealing with mixing boxes.)

The tool is designed to be run on a lap-top computer. The tool can be configured with the necessary design information and catalog data either on-site before or in the course of the testing or off-site, e.g. in the commissioning agent's office prior to going on site. In the future, it is anticipated that such tools, both semi-automated and automated, will be able to be configured automatically by downloading design information and catalog data from the web, and there are a number of possible approaches.to accessing these project data. A first step towards this end is being taken by a developing a prototype tool that extracts equipment data in the format of the Industry Foundation Classes (IFC), developed by the International Alliance for Interoperability (IAI 2006) from a database and reformats for use in the tool described here.

The modules developed to date test the operation of the mechanical equipment in built-up systems, including the sensors and actuators, by comparing the expected and observed steady state behavior of the supply fan, the return fan, the mixing box and the heating and cooling coils. The tests can be performed in open loop, by overriding the control signal to the actuator, or in closed loop, by changing the appropriate set-point. Open loop tests do not test the operation of the controller; however, they do not rely on the controller being correctly configured and tuned in order to test the mechanical equipment. Closed loop tests for the supply air temperature loop and the supply static pressure loop are being developed but will not be described here.

ANALYSIS METHOD

The tool analyzes the opertation of the equipment under test by comparing the measured behavior to the expected behavior at the operating points used in the test as predicted by a mathmatical model configured using design information and catalog data. Significant differences between the measured and expected performance at one or more operating points indicate the presence of one or more faults. Faults are diagnosed by analyzing the deviation of the measured performance from the expected performance at the different operating points using expert rules. Fuzzy inferencing is used as a convenient and intuitive way to relate linguistic rules to continuous systems. The analysis method used in the tool is described in more detail in (Xu *et al.* 2005). The models used to define correct operation are now described, together with the input data required to configure them.

Fan Temperature Rise

The value of the supply fan temperature rise is required in order to predict the mixed air temperature and the off-coil air temperatures from the supply air temperature. Off-coil air temperature sensors are typically not present and measurements of mixed air temperature are often unreliable due to poor mixing of the outside air and return air streams. The value of the return fan temperature rise is required in order to predict the recirculation air temperature from the return air temperature when the return air temperature is upstream of the return fan. The temperature rise is calculated by equating the increase in the sensible heat content of the air stream to the sum of the fluid work done by the fan and the heat produced by the inefficiency of the fan and other associated components:

$$\Delta T = \frac{\Delta P}{\rho c_p \eta} \tag{1}$$

where ΔP is the total pressure rise across the fan, ρ is the density of air, c_p is the specific heat of air, η is the combined efficiency of the fan components in the air stream (typically the fan, belt and motor). The total pressure rise across the fan can either be measured directly or it can be inferred from the flow rate. For the supply fan in a VAV system, this is done by equating the pressure rise across the fan to the sum of the pressure rise between the air inlet to the air handling unit and the position of the static pressure sensor and the pressure drop across the components between the inlet and the pressure sensor. In the approximate calculation used in the tool, the pressure in the mixing plenum is assumed to be independent of the position of the dampers. The pressure rise across the supply fan is then:

$$\Delta P = P_{set} + \frac{\rho V^2}{2A^2} + R_{up} V^2 \tag{2}$$

where P_{set} is the supply duct static pressure set-point, V is the volumetric flow rate, A is the cross sectional area of the supply duct at the position of the sensor and R_{up} is the resistance of the duct system upstream of the static pressure sensor (including coils, filters, attenuators etc). The second term on the right hand side is the velocity pressure at the sensor and the third term is the pressure drop across the components other than the fan. At design conditions, Equation 2 becomes:

$$\Delta P_D = P_{set} + \frac{\rho {V_D}^2}{2A^2} + R_{up} {V_D}^2 \tag{3}$$

where ΔP_D is the design pressure rise and V_D is the design flow rate. Substituting Equation 3 into Equation 2 and the resulting equation into Equation 1 yields:

$$\Delta T = \frac{1}{\rho c_p \eta}\left[P_{set}(1-\frac{V^2}{V_D^2}) + \Delta P_D \frac{V^2}{V_D^2}\right] \tag{4}$$

which depends only on design information, properties of air and the air flow rate. For the purposes of calculating the fan temperature rise, the sum of the flow rates measured by the VAV boxes, if available, is probably a sufficiently accurate measure of the flow rate through the fan, particularly if it has been checked, and a correction factor determined, as part of a recent testing and balancing. The velocity pressure term in Equations 2, $\rho V^2/2A^2$, vanishes, eliminating the need for the user to determine and enter the duct cross sectional area, A.

Fan Capacity and Efficiency

The fan model is a simplified model that approximates the *active* part of the head curve by a two term quadratic:

$$\Delta P = P_0 n^2 - R_{fan} V^2 \tag{6}$$

where the first term is the pressure rise extrapolated to zero flow rate and the coefficient of the second term, R_{fan}, can be thought of as the internal resistance of the fan. Since there are two parameters, two catalog data points are required for the tool. For a VAV system, if one point corresponds approximately to the design point (Point 1 in Figure 1), a useful rule of thumb is that a point on the same speed curve with two thirds the flow rate corresponds to a turn-down of ~4:1 when the ratio of the design pressure rise to the static pressure set-point is 4:1 (Point 2 in Figure 1). Tabular data, if available, are more convenient and more accurate than values read from the curves. Selecting the nearest tabular data to the selected points is satisfactory, since the purpose is to approximate the head curve over the active range. The tool uses the efficiency calculated at the higher flow rate as the reference efficiency for comparison with the measured efficiency. Since the efficiency can be expected to be slightly lower at the higher flow rate (Point 1 in Figure 1), this minimizes the danger of false positives in the detection of efficiency faults.

Cooling Coil

The underlying model is a variant of the ‘detailed’ model in the ASHRAE HVAC Secondary Toolkit (Brandemuehl 1994), which treats partly wet conditions by iterating to find the position of the boundary between the wet and dry regions of the coil. The Secondary Toolkit model has been extended in two ways:

- the air and water-side film resistances depend on the fluid velocities, rather than being constant, and
- while the overall UA is determined from a design condition rating point, as usually presented in the coil schedule on the mechanical drawings, the ratio of the air-side and water-side film resistances is determined from empirical correlations presented by Holmes (1982).

The first extension allows the model to treat variations in airflow rate and water flow rate more accurately and the second allows rating points for which the coil is dry or partly wet to be used to configure a model that not only treats the dependence of the overall UA on the fluid velocities but also predicts the surface temperature in order to treat condensation. Methods that estimate the air-side and water-side resistances from a single rating point by calculating the apparatus dew point temperature and the by-pass factor are only valid for coils that are fully wet at the rating point.

Holmes (1982) models the overall UA of a dry coil as:

$$\frac{1}{UA} = \frac{1}{A_{face} n_{row}}\left[a_1 v_{air}^{-0.8} + a_2 + a_3 v_{water}^{-0.8}\right] \tag{7}$$

where A_{face} is the face area, n_{row} is the number of rows, v_{air} is the air velocity and v_{water} is the water velocity. Representative values of the empirical constants a_1, a_2 and a_3 are given in Holmes' paper for different types of heating coil and cooling coil, e.g. closely or widely spaced fins, with or without turbulators. An issue arises regarding the interpretation of second, a_2, term. The significance is that it affects the calculation of the surface temperature in contact with the air, and hence the condensation rate. The form of Equation 7 suggests the identification of the second, a_2, term with the resistance of the metal of the coil; the first and second terms are similar in magnitude under typical design conditions, suggesting that the second term represents at least some of the fin resistance (the usual practice in coil modeling is to include the fin efficiency as a mulplicative factor in the the air-side conductance). An alternative interpretation is that the effective magnitude of the exponent of the air velocity decreases with decreasing velocity, the flow not being fully turbulent (Reynolds number ~200-1000, flow regime determined by entry effects and the effect of the tubes). Fitting measured data to Equation 7 can be expected to produce increased values for a_2 to compenstate for the fixed, relatively large magnitude of the exponent of the v_a term. The model in the tool assumes that the a_2 term represents part of the air-side resistance.

Use of a model based on Equation 7 requires calculation of the fluid velocities from the available measurements, i.e. volumetric flow rates. In the case of the tool described here, it is not necessary to evaluate the $1/A_{face}n_{row}$ term since only the relative magnitudes of the three terms inside the square brackets is of interest.

The same approach is used to configure the heating coil model. The number of rows is use to determine the appropriate effectiveness-NTU relationship to use in the model. For a one row coil, cross flow with the air unmixed and the water mixed is assumed. For a two row coil, the relationship for cross flow with both fluids unmixed is used as pragmatic compromise between cross flow and counterflow.

Mixing Box

As shown in Figure 2, the ideal response is taken to be a linear relationship between the outside air fraction, *OAF,* and the control signal, *u*. The outside air fraction is related to the temperatures in the mixing box by:

$$OAF = \frac{(T_{ret} - T_{mix})}{(T_{ret} - T_{out})} \times 100\% \tag{8}$$

where T_{ret} is the return air temperature, T_{mix} is the mixed air temperature and T_{out} is the return air temperature.

Two parameters define the acceptable range of operation, the maximum acceptable deadzone between the control signal coming out of a limit and the damper starting to move so as to affect the air flow, DZ_{max}, and the maximum acceptable deviation from linearity at the mid-point of the active range, ΔOAF. These values are generally not specified and so must be defined using engineering judgement, taking into account how critical the application is. Reasonable default values are DZ_{max} = 10% and ΔOAF=25%.

The exact form of the relationships used to specify the upper and lower limits of acceptable mixing box performance are somewhat arbitary, being chosen for mathematical convenience:

$$\text{Lower limit:}\quad \begin{aligned} OAF_{low} &= \left(\frac{u - DZ_{\max}}{100 - DZ_{\max}}\right)^{x} \times 100 & u > 100 - DZ_{\max} \\ &= 0 & u \le 100 - DZ_{\max} \end{aligned} \tag{9a}$$

$$\text{Upper limit:}\quad \begin{aligned} OAF_{high} &= \left[1 - \left(1 - \frac{u}{100 - DZ_{\max}}\right)^{x}\right] \times 100 & u < DZ_{\max} \\ &= 100 & u \ge 100 - DZ_{\max} \end{aligned} \tag{9b}$$

where

$$x = \frac{\log(\frac{50 - \Delta OAF}{100})}{\log(\frac{50 - DZ_{\max}}{100 - DZ_{\max}})} \tag{10}$$

Both DZ_{max} and ΔOAF must be in the range 0-50%.

FAULT DIAGNOSIS

Expert rules that provide limited diagnosis of common faults have been implemented in the tool. The rule bases for the different components are being refined in response to the results of on-going testing. The rules used to date are based on the considerations described in this section.

Fan Capacity and Efficiency

The first step in the diagnosis phase is to check if the ratio of the pressure rise to the square of the flow rate lies between the values of this ratio corresponding to the two catalog rating points used to configure the model. If it lies outside, this indicates that the catalog rating points were selected or entered incorrectly or that there is a distribution system problem or a measurement problem. If the static pressure fails to attain set-point and the rotation speed is below design, the motor may be the wrong speed/incorrectly sheaved or undersized. Next, the measured efficiency is calculated from the measured flow rate, pressure rise and electric power and the differences between the measured and expected capacities and efficiencies used to provide some discrimination between the different possible faults. Five cases are considered:

- **Capacity is low, efficiency is normal:** fan is undersized
- **Capacity is normal, efficiency is low:** reduced VFD, motor or belt efficiency (if the capacity of the fan is normal, its efficiency is likely to be normal too)
- **Capacity is low, efficiency is low:** reverse rotation, damaged fan, excessive system effect
- **Capacity is high, efficiency is normal:** oversized fan
- **Efficiency is high:** probable sensor or measurement error (also a possibility in the cases listed above)

Other cases, e.g. high capacity and low efficiency, could be caused by multiple sensor faults.

Mixing Box

Sensor and leakage faults. An offset in the supply air temperature sensor calibration produces a difference between the measured and expected supply air temperature. If the outside temperature is lower than the return temperature, a return air temperature sensor that reads low produces a similar response to a leaking outside air damper and an outside air temperature sensor that reads high produces a similar response to a leaking return air damper. If the offsets are in the opposite direction, their effect is first to mask damper leakage and then produce supply air temperature measurements that cannot be explained by other faults. These offset and leakage faults can be separated by repeating the test when the difference between the outside and return air temperatures is much smaller, or even reversed.

Nonlinearity and hysteresis faults. The uncertainty in the expected performance in the middle of the range is relatively large, reflecting a tolerance for non-linearity that is not judged to be so extreme as to cause control difficulties. Detection of hysteresis then relies on the direct comparison of the measured outside air fraction opening and closing, rather than a comparison of each of these quantities with the expected value.

Coils

The structures of the functional tests for the mixing box and the coils are similar and the fault diagnosis approach is similar.

Sensor and leakage faults. Considerations similar to those for mixing boxes apply to coils. For heating coils, an overestimate of the inlet air temperature has a similar effect to a leaking control valve, whereas an underestimate first masks control valve leakage and then produces a lower than expected supply air temperature. An overestimate of the inlet air temperature or an underestimate of the inlet water temperarture produces an overestimate of the capacity, and vice versa. The same logic can be applied to cooling coils, with reversed results. In principle, measurements with the valve closed, half open and fully open can be used to separate the effect of leakage, capacity faults and air temperature sensor faults. In practice, the uncertainies in the expected supply air temperatures when the valve is open mean that only large air temperature sensor faults can be diagnosed unambiguously.

Nonlinearity and hysteresis faults. Considerations similar to those for mixing boxes apply.

SOFTWARE STRUCTURE

Figure 3 shows the internal structure of the software. At the top of the diagram is the data entry module which handles manual entry of test measurements from the system under test. The data are then passed through a preprocessor where they are checked and converted into the appropriate units. After the data for each new test step are entered, they are processed by the analysis modules. On the right side of the diagram is the SPARK simulation tool (SPARK 2006) that uses a model of the system under test to predict the correct operation performance. The comparator is used to compare the simulated and measured performance and generate fault alarms. The fault diagnosis module uses IF-THEN rules and fuzzy inferencing to generate fault diagnoses. Fuzzy logic is a convenient method of applying linguistic rules to continuous systems.

USE OF THE TOOL

Configuring the Tool – Site and Air Handling Units

The use of the tool will now be described, illustrated by example screen images. How the configuration data relate to the models used to define expected performance is discussed in a subsequent section. The first step is to specify the characteristics of the site, which could be a single building or a group of buildings, such as a campus. As shown in Figure 4, these characterisitics include the elevation, used to calculate the approximate density of the air, and whether the chilled water contains glycol and, if so, its type and concentration. Both of these characteristics are used in calculating the expected performance of the cooling coil and the air density is also used in calculating the expected performance of the fans and the heating coil.

The next step is to specify the name and characteristics of each of the AHU's to be tested. If there are multiple buildings on the site, the name should include the name of the building. The characteristics, which are mainly used to estimate the effect of fan temperature rise on the functional tests of the thermal components, are shown in Figure 5. The position of the supply fan, before or after the coils, determines whether the supply fan temperature rise should be added when infering the coil inlet air temperature from the outside or return air temperature or subtracted when inferring the coil outlet air temperature from the supply air temperature. (It is assumed that the mixed air temperature sensor, if it exists, is unreliable.) The position of the fan motor determines whether the inefficiencies of the motor and the belt contribute to the fan temperature rise.

Configuring the Tool – Components

Fan. Figure 6 shows the configuration screen for a fan subsystem. Two catalog data points are required for the fan itself, together with efficiency values (assumed constant) for the motor, belt and VFD. The design rotation speed, turndown and control signal information are required to check the set-up and linearity of the VFD.

Cooling and Heating Coils. Figure 7 shows the configuration screen for the cooling coil. The rating point information from the coil schedule is supplemented by information required to calculate the air and water velocities from the corresponding volumetric flow rates, the use of which is explained in the section on modeling and input requirements. The face area is required to calculate the air velocity and the number of circuits and the tube diameter are required to calculate the water velocity. The number of circuits may be difficult or time-consuming to determine in some situations; in such cases, the tool can use a default value of 6 ft.s^{-1} (2 m.s^{-1}) for the water velocity under design conditions. The maximum acceptable deadzone between the control signal coming out of a limit and the valve starting to move so as to affect the water flow is used in the test for incorrect adjustment or range mismatch of the control valve and the actuator. The maximum acceptable deviation from linearity at the mid-point of the active range is used to check for poor authority or incorrect control valve characteristic.

The input configuration process for heating coils is similar to that for cooling coils, expect in two respects:

- the humidity information is omitted
- the number of rows is included for use in determining the appropriate effectiveness-NTU relationship to use in the model.

Mixing Box. The mixing box model is purely prescriptive; no attempt is made to simulate the expected performance based on the damper characteristics and AHU geometry. The only configuration data required by the tool are:

- the maximum acceptable deadzone between the control signal coming out of a limit and the dampers starting to move so as to affect the air flow
- the maximum acceptable deviation from linearity at the mid-point of the active range as discussed above.

As in the case of the coils, these values must be defined using engineering judgement, based on the application. The default value for the maximum acceptable deadzone is 10% and the default value for the maximum acceptable deviation from linearity is 25%, which corresponds to a variation in gain between the upper and lower halves of the operating range of 3:1.

Functional Testing

The tool has been designed to analyze the results of tests of specific mechanical components that consist of a series of steps in operating point, as described by Xu *et al.* (2005). The preferred sequence for testing the different components is to start with the fans. Correct operation of the supply and return fans is necessary for correct pressures in the mixing box. The calculations of the temperature rise across the supply fan and the return fan, which are used to correct to correct the supply and return air temperature measurements in the tests of the mixing box and the coils, also depend on the correct operation of the fans. The mixing box should be tested before the coils, since damper leakage could cause the actual mixed air temperature, and hence coil entering temperature, to differ from the assumed value based on the position of the dampers and the measurement of outside or return air temperature. If both a heating coil and a cooling coil is installed, the order of testing is immaterial, as long as the coil not under test can be turned off effectively, e.g. with isolating valves.

Fan capacity and efficiency. Figure 8 shows the screen for the testing of fan capacity and efficiency. The control signal to the VFD, the rotation speed, the flow rate, the pressure rise and the electric power are entered by the user and the date and time are generated automatically by the tool. In general, not all of these measurements will be available from the EMCS and portable instruments will be required for some measurements. The fan model embedded in the tool predicts the pressure rise and electric power from the rotation speed and he flow rate, using the catalog data entered in the configuration phase, and these are then displayed, along with uncertainties estimated using assumptions about the accuracy of the measurements that are hard-coded into the tool. The purpose of the tool is to detect and diagnose substantial faults; more accurate acceptance testing procedures are described in ASHRAE *Standard* 51 / AMCA *Standard* 210. The tool compares the measured and expected pressure rise and electric power. If either of the differences exceeds the combined uncertainties, a fault is reported.

The top section of the window is where performance and analysis data are entered and displayed. Data can be entered after each step of the functional test sequence or all the data can be entered together at the end of the sequence, whichever is more convenient for the user. If the data are entered after each step, the tool can analyze the data entered up to that point in time and potentially flag a major fault that would render it pointless continuing with the test.

The section in the middle of the window is used to show the progress of the tests and to display the final test report. The tool can also generate a report in text format for printing. The test report consists of three parts. The first part contains general information about the test and also the performance data entered by the user. The second part shows the fault analysis at each step. The last part is a summary of the results of the complete test, including a numerical measure of the confidence that the operation is correct or incorrect and that particular faults have been diagnosed.

The section at the bottom of the window provides guidance on the test sequences. The users can easily switch between the action description, the explanation, and what to expect sections.

VFD. The set-up and linearity of the VFD is tested by commanding three different fan speeds, maximum, mid-range and minimum, and measuring the resulting rotation speeds. The values are entered into the tool, which then checks for a linear relationship between measured rotation speed and control signal. The mid-range signal is approached from above and below and the resulting rotation speeds compared to check for hysteresis.

Cooling coil and heating coil. The coils are tested using a procedure similar to that described in Xu *et al.* (2004) and illustrated in Figure 9. Testing for a significant temperature increase or decrease across the coil at control signal u=0 (Step 1) checks for control valve leakage. Testing for a significant change at $u=DZ_{max}$+5% (Step 2) checks that the valve has started to open within the maximum acceptable deadzone, DZ_{max}, 5% being a sufficient change in control signal to detect a change in temperature increase or decrease across the coil. Tests at u=50% opening and closing (Steps 3 and 6) are used to check for gross non-linearity and for hysteresis. Tests at u=100% and u=100-(DZ_{max}+5)% (Steps 4 and 5) check for an unacceptable deadzone at the open end of the operating range. These tests are performed at minimum airflow in order to maximize any temperature increase or decrease across the coil and to minimize the temperature rise across the supply fan, which must be corrected for when estimating the coil leaving air temperature. A test at u=100% (Step 7) checks the capacity; this test must be performed at close to the design airflow rate. The measurement of airflow rate used for the capacity test should be as accurate as possible; water-side flow rate and temperature difference measurements may provide higher accuracy and/or provide a consistency check, The airflow rate measurement for the other steps is less critical, since the aim is to detect significant control valve leakage, for example, rather than to measure its magnitude accurately. An estimate of airflow rate obtained by summing the reported flow rates from the VAV terminal units should be sufficiently accurate. Alternatively, measurements of supply fan speed and power or pressure rise (depending on the type of fan) can be used to estimate the flow rate from the installed characteristics of the fan established in the fan test. Use of a semi-automated tool allows the use of temporary humidity sensors in the cooling coil test; the requisite humidity measurements typically being unavailable from the EMCS.

Mixing box. Figure 10 shows the functional test screen for the mixing box. The test procedure is similar to the coil test procedure, except that the test at u=100% (i.e. outside air damper fully open) is used to check for leakage of the return air damper and there is no need for Step 7; the whole test can be performed at minimum airflow rate in order to minimize the temperature rise across the fans and the uncertainty in estimating the corresponding correction to the return and supply air temperatures. The measurements shown in Figure 10 were made during one of the functional tests performed as part of the field testing described below. Figure 11 shows data collected during this test with a sampling interval of one minute. In principle, the primary criterion for having reached steady state is that each of the measured inputs and outputs for the component or subsystem under test, in this case, the quantities plotted in Figure 8, should change by an amount that is small compared to the overall uncertainty in that quantity. In practice, other considerations apply; for example, during the period between 5:35 and 5:50, the return air temperature was increasing at an approximately constant rate in response to the increase in supply air temperature. The user made the decisions to proceed to the u=10% step and the u=50% step because the outside air fraction, which defines the performance of the mixing box, had stabilized to an acceptable degree. This criterion should be used with caution when the system has significant dynamics. In the case of the mixing box test, the thermal capacity of the coils, which are located between the mixing box and the supply air temperature sensor, determines the dynamic response of the supply air temperature, as illustrated by the approximately exponential variation of the supply air temperature between 5:50 and 6:00. If a mixing box has been designed to produce good mixing and/or a carefully installed averaging sensor for the mixed air temperature is available, the mixed air temperature measurement can be used directly instead of using the supply air temperature measurement as a proxy for the mixed air temperature. However, these conditions are fulfilled relatively rarely and, in any case, should not be assumed in functional testing. Further field testing is required to refine the steady state criteria.

Figure 12 shows the plot screen, which consists of two charts, for the case of the mixing box. The upper chart shows the control signal, the measured inlet conditions and the measured and expected outlet conditions at each step of the test. The lower chart shows the measured and expected normalized outputs – outside air fraction in the case of the mixing box – with error bars indicating both the predicted uncertainty due to measurement error and the range of acceptable performance. Measured and expected values whose error bars just fail to overlap indicate a fault at a significant confidence level; a greater separation indicates a higher level of confidence. The measurements indicate significant differences between the expected and measured performance at u=90% and u=100%, indicating a leaking return air damper, or possibly a miscalibrated or poorly positioned outside air temperature sensor. The diagnosis generated by the current version of the tool, shown in Figure 10 is incomplete in that it does not include the possibility of the outside air temperature sensor reading being incorrect. One advantage of a diagnosis method based on rules is that new rules can be added relatively easily; new rules relating to the outside and return air sensors will be added to the rule-base, which already includes rules relating to the supply air temperature sensor, in the next version of the tool.

DEVELOPMENT AND TESTING

An 'alpha' version of the tool was tested at an experimental facility that includes a matched pair of well-instrumented air handling units. The staff of the facility introduced artificial faults into the AHU's in a manner similar that employed in ASHRAE 1020-RP (Norford *et al.*2002). The data collected during a summer period and a winter period have been used in subsequent testing of tool as it has evolved. The staff also provided feedback on the design of the tool and the user interface. The tool will then be tested by two groups of commissioning agents, one in California and one in New York State, with further refinements after each round of testing.

SUMMARY

A software tool for functional test data analysis has been developed. The tool uses generic step test sequences to detect and diagnose major faults of mechanical components, including sensors and actuators, in air handling units. The use of embedded models allows testing to be performed at off-design conditions. The models have been selected to minimize the need for configuration data not normally provided on mechanical drawings. Fault detection is performed by comparing the measured performance to that predicted by the model. Fault diagnosis is performed by analyzing the variation with operating point of the deviation from expected performance using expert rules and fuzzy inferencing. The tool is semi-automated, in that the data analysis and fault diagnosis are automated but the performance data need to be entered manually. The tool is in public domain and will be freely available at the end of the development and testing process.

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Figure Captions

Figure 1 Load lines and fan curves for design flow rate and maximum turn-down for the supply fan in a VAV system

Figure 2 Acceptable range of mixing box response

Figure 3 Data analysis software tool internal structure

Figure 4 Site Description window

Figure 5 AHU Configuration window

Figure 6 Fan configuration screen

Figure 7 Cooling coil configuration screen

Figure 8 Fan functional test screen

Figure 9 Functional test steps for coils and mixing boxes

Figure 10 Mixing box functional test screen

Figure 11 Trend plot recorded during a functional test on a mixing box

Figure 12 Mixing box graphical output