Fault Detection & Diagnostics

For AHUs and VAV Boxes

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Building HVAC equipment routinely fails to satisfy performance expectations because of improper installation, inadequate maintenance, or equipment failure. These problems include mechanical failures such as stuck, broken, or leaking valves, dampers, or actuators; control problems related to failed or drifting sensors; poor feedback loop tuning or incorrect sequencing logic; degraded performance caused by heat exchanger fouling; design errors; or inappropriate operator intervention.

These faults often go unnoticed for extended periods until the deterioration in performance becomes great enough to trigger comfort complaints or a gross equipment failure. The term fault detection and diagnostics (FDD) refers to mathematical techniques to detect and diagnose these types of faults.

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By identifying and diagnosing faults to be repaired, FDD techniques can benefit building owners by reducing energy consumption, improving operations and maintenance (O&M), and increasing effective control over environmental conditions in occupied spaces. A number of studies estimate that FDD has an energy-saving potential of 10% to 30%, depending on the age and condition of the equipment, maintenance practices, climate, and building use.[1,2,3,4]

Significant non-energy benefits of FDD exist. By identifying minor problems before they become major problems, the useful service life of equipment can be extended. Also, repairs can be scheduled when convenient, avoiding undesirable downtime and costly overtime work. Depending on building use, better control of the temperature, humidity, and ventilation rate of the occupied spaces can improve employee productivity, guest/customer comfort, and/or product quality control. In some cases, identifying and repairing faults may make the difference between regulatory compliance and noncompliance.

A number of FDD tools are emerging from research.[5,6] In general, these tools take the form of stand-alone software products where trend data files must be processed off-line or an interface to the building control system must be developed to enable on-line analysis.

A different approach is to embed FDD in the local controller for each piece of equipment, so that the FDD algorithm is executed as a component of the control logic. In this case, the algorithm will have local access to sensor data and control signals, eliminating the need to communicate this information over the building control network.

This approach is highly scalable, and, therefore, suitable to larger HVAC systems. Any faults that are detected can be reported to the building operator using the building automation system's alarm or event handling capability.

This article discusses two FDD methods: AHU Performance Assessment Rules (APAR) and VAV box Performance Assessment Control Charts (VPACC). APAR and VPACC can detect common faults in air-handling units (AHUs) and variable-air-volume (VAV) boxes, respectively. The tools are sufficiently simple that they can operate, alongside the control logic, within the processor and memory limitations of commercial HVAC equipment controllers. APAR and VPACC produce outputs that are meaningful to building operators and robust against false alarms.

AHU Performance Assessment Rules (APAR)

APAR evaluates a set of rules to determine the presence of faults. These rules are based on simple mass and energy balances of various subsystems of an AHU.[7] The APAR algorithm is a three-step process: in Step 1, the mode of operation is determined, based on the positions of the heating coil valve, cooling coil valve, and mixing box damper; Step 2 follows with the evaluation of the rules applicable to the current mode; and in Step 3, possible diagnoses of the fault are listed.

APAR is applicable to single duct VAV and constant volume AHUs with airside economizers (*Figure 1*). The operation of this type of AHU during occupied periods can be classified into a number of modes, depending on the heating/cooling load and outdoor air conditions (*Figure 2*). Each mode of operation can be characterized by different ranges of values for each of three control signals: the heating coil valve, cooling coil valve, and mixing box dampers. The modes are heating (Mode 1), cooling with outdoor air (Mode 2), mechanical cooling with 100% outdoor air (Mode 3), and mechanical cooling with minimum outdoor air (Mode 4).

APAR has a total of 28 rules. Each rule is expressed as a logical statement that, if true, indicates the presence of a fault. Because the mass and energy balances are different for each mode of operation, a different subset of the rules applies to each mode. Some rules are independent of the operating mode and are always evaluated. *Table 1* shows the set of rules that are specific to Mode 2, cooling with outdoor air.

Rule 7 from *Table 1* illustrates how the APAR rules were developed. This rule is based on an energy balance of the coil subsystem. In Mode 2, both the heating and cooling coil valves are closed, so the outlet (supply air) temperature should be equal to the inlet (mixed air) temperature plus the heat addition from the supply fan. Possible diagnoses associated with this rule are supply air temperature sensor error; mixed air temperature sensor error; leaking cooling coil valve; cooling coil valve stuck open, partially open, or closed; leaking heating coil valve; or heating coil valve stuck open, partially open, or closed.

It is typical of APAR rules that several different faults can cause a single rule to be violated. As a consequence, a few simple rules can be used to find many different faults. Although a list of candidate faults can be made based on the violated rule(s), further information, such as a plot of trend data, is usually needed to identify the specific cause of the fault.

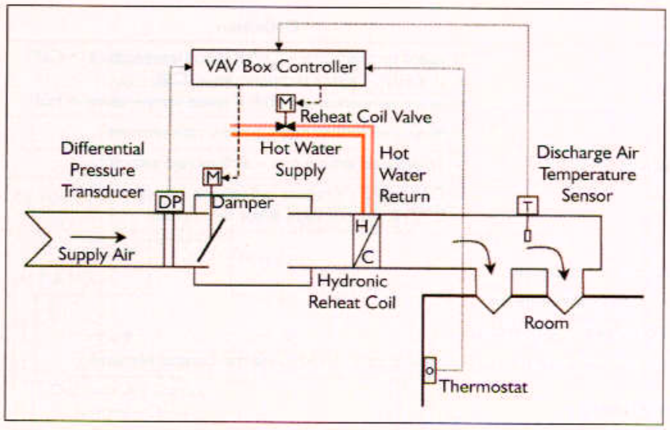

Figure 5: VAV box schematic.

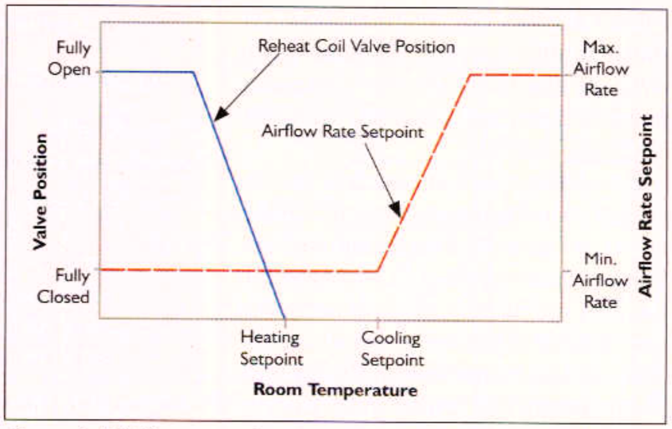

Figure 6: VAV box control sequence.

process errors were defined that are meaningful to these systems (*Table 3*). VPACC works by applying the CUSUM technique to each of the errors in *Table 3*.

Figure 7 shows a plot of data collected during a laboratory test of VPACC.[11] An unstable airflow fault was created by altering a parameter in the controller logic to induce oscillation in the damper position. The airflow rate error varies between positive and negative, so the fault is detected by the absolute value of the airflow rate error S (positive) cumulative sum, which increases to the alarm limit, h (set at 900) twice during one day of operation. When the sum reaches h, an alarm is recorded and the sum is reset.

VPACC also can be applied to other VAV box types or to VAV boxes without discharge air temperature sensors by selecting a different combination of process errors.

APAR and VPACC Commercialization Issues

The ability of APAR and VPACC to detect a variety of faults with varying severity and during various weather conditions has been evaluated using simulation, building emulation involving commercial building controllers, and limited field tests.[8,10,11,12] The results of those studies indicate that APAR and VPACC were successful at finding a variety of faults including stuck or leaking dampers and control valves, sensor drift, and improper control sequencing.

The simplicity of APAR and VPACC is a considerable advantage over other FDD techniques since they can be implemented in existing commercial controllers. This has been tested and verified for a small sample of controllers using only the programming software usually provided with the products.[11] The deployment path envisioned for APAR and VPACC is for manufacturers to include these FDD tools in their standard application program libraries.

One obstacle to commercialization is the lack of a simple means to establish the fault thresholds and statistical parameters that the tools need. A fault threshold expresses the severity of a fault required to trigger an alarm, and is necessary because of uncertainty in the data and operating conditions. If the threshold is too low, normal variation in the data and operating conditions may trigger false alarms. If the threshold is too high, only the most severe faults will be detected.

At this time, the fault thresholds and statistical parameters are determined on a case-by-case basis for each site. This requirement for site-specific configuration is unlikely to succeed as a general practice. A field study is underway, in cooperation with several control system manufacturers, to test APAR and VPACC in a variety

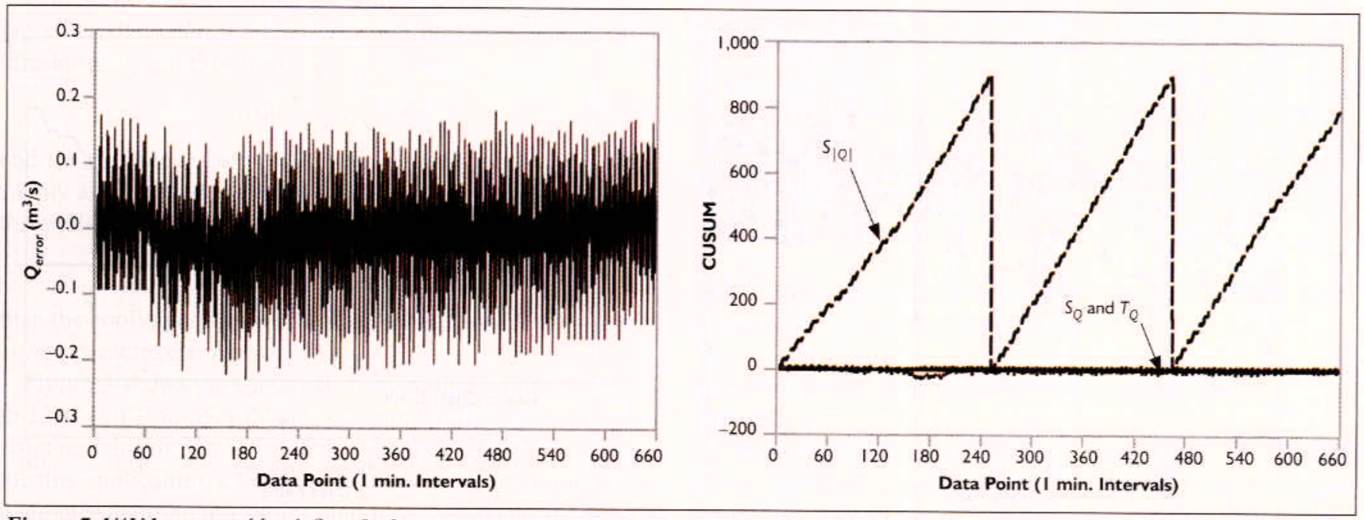

Figure 7: VAV box unstable airflow fault.

of systems with the intent to develop some simple guidelines that can be used to establish fault thresholds and statistical parameters that will eliminate the need for site-specific configuration.

Summary

The increasing performance demands on building automation and control systems, combined with the growing complexity of these systems, have created a need for automated FDD tools.

Tools that can be embedded in the controllers offer significant advantages over approaches that depend on collecting and analyzing large amounts of trend data. Two such tools, APAR and VPACC, have been shown to be effective in detecting common AHU and VAV box faults.

Work underway in collaboration with several control system manufacturers is expected to establish guidelines to eliminate the need for site-specific customization and lead to new FDD capabilities that will be offered in those manufacturers' standard program libraries.

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