UNCERTAINTY IN THE PERFORMANCE VALIDATION OF HVAC SYSTEMS

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ABSTRACT

A first principles based model approach to AHU cooling coil performance validation is presented. The model of correct operation is compared to that observed in the real system. In the scheme, uncertainty in the measurements and the models is evaluated to generate robust thresholds for decision making. The approach describes the design intent by estimating certain model parameters from design data and expert knowledge. The method systematically incorporates the uncertainty in these parameter estimates in the calculation of the system validation threshold. This yields a definite, transparent indication of system performance to a stated level of confidence. The approach is demonstrated on a cooling coil subsystem installed in an air-handling unit serving zones in a real building.

KEYWORDS: Fault detection, performance validation, automated commissioning.

INTRODUCTION

Between 15% and 30% of the energy consumed by buildings is wasted though sub-optimal system operation (Katipamula and Brambley, 2005). Performance validation is important to ensure systems are operating as the intended by the design. HVAC equipment should be installed, sized and commissioned correctly to ensure that the desired environmental conditions can be met, will not waste energy in operation and will be controllable. Recent research projects have demonstrated that it is quite common to find systems operating sub-optimally (Norford et al, 2000, Buswell et al, 2003). Problems include, undersized coils, non-linear performance characteristics, excessive control valve dead bands and hysteresis.

Conventional performance validation techniques are typically single point verification of system performance, such as maximum coil duty. It is difficult to apply these methods to part load operation, which are generally prevalent in HVAC operation. Model based approaches to performance validation are useful because they allow comparisons over a range of operating conditions (Buswell et al, 2000, Salsbury and Diamond, 2000).

This paper presents a first principles model based approach to performance validation. Data across the range of operation of the sub-system is collected and compared to a model who's parameters are adjusted to represent the design intent. The differences between the data and the model predictions, the residual, is used to identify correct/incorrect operation. The difficulty with real systems is identifying when the magnitude of the residual is significant. The approach here considers uncertainty; in the measurements, model structure and in the model the parameters used to represent the design intent. The approach is demonstrated on a cooling coil subsystem installed in a real building and it is shown that it yields a definitive, transparent, robust threshold for decision making.

UNCERTAINTY IN PERFORMANCE VALIDATION

The advantage of first principles based models is that the parameters can be designed to represent meaningful values. Certain parameters are used to incorporate the system design data. The model then represents the system characteristics of the system as it was designed. Combined with systematic data collection from the test system, the model predictions are compared with the measured response and a residual is generated. There will always be some difference, it's the magnitude of the difference that is important. The method used here is to calculate the 95% confidence limits of the residual by evaluating the uncertainties described in Table 1. The novelty here, is recognising that there is some uncertainty in the model structure (Buswell, 2001) and in treating the selection of the model design parameters as estimates with a degree of uncertainty. This allows the design intent and compliance with standards and best practice to be described in this way. It can then be incorporated into the overall calculation of uncertainty in the residual. The confidence limits, therefore embody the uncertainty in the interpretation of the design intent and are therefore robust indicators of system compliance.

Table 1: Sources of Uncertainty Associated with Performance validation System.

Measurements	**Model Structure**	**Design Intent**
sensor	Detail	standards
data handling	Assumptions	interpretation
noise	form	judgement

Using the method established by Kline and McClintock (1953), the uncertainty in the system output can be estimated by,

$$U_y^2 = B_y^2 + P_y^2 + R_y^2 + D_y^2, \quad (1)$$

where, U_y is the 95% estimate of uncertainty in the residual, y. B represents the estimate of the bias uncertainty present in the measurements. P represents the random uncertainty in the measurements. R represents the uncertainty in the model structure and D represents the uncertainty in the parameters used to describe the design intent. All four contributions are estimated at the 95% confidence level. Correlations in the measurement bias uncertainty are accounted for. A fixed time window is used to evaluate the random component.

There are two models used in the scheme; an *SHR* and *NTU* water to air heat-exchanger model (based on the Holmes (1982) model) and a first principles based model of a three port control valve and actuator. The models are similar to those in Buswell et al. (2002). Buswell, 2001 has demonstrated that uncertainty exists in the model structure i.e: cross-flow/counter-flow approximation in the HVAC class of coil; physical constants; fluid flow regimes; resistance (to heat transfer) parameters; treatment of mass transfer, and a full discussion is available in Buswell (2001),

Incorporating the Design Intent Tolerance

The design intent is defined as the required output of the whole subsystem in terms of the linearity and duty characteristics. The subsystem must:

- meet the specified capacity;

- have a nominally linear gain;
- have no load when the control valve is closed (control port leakage);
- have no significant restrictions in the operation range (dead bands);
- have an insignificant level of hysteresis;

Tables 2-4 detail the parameter values used in this study. Table 2 gives the relationships between the model parameters and the design intent. Table 3 details the parameters required to specify a particular system. Table 4 gives the uncertainties (first 10) and design intent tolerances (last 6) on the model parameters described in Tables 2 and 3.

Table 2: The Model Parameter and the Design Intent.

Design Intent	**Model Parameter**	**Value**	**Unit**
Specified capacity	Tube Material Resistance	0.417	WK^{-1}
	Waterside Resistance Coeff.	0.28	$(rows)m^2s^{-0.8}W^{-1}m^{0.8}$
	Airside Resistance Coeff.	1.033	$(rows)m^2s^{-0.8}W^{-1}m^{0.8}$
Nominally linear gain	Valve Authority	0.5	-
	Valve Curvature	4.5	-
No load when valve is closed	Valve Leakage	0.0	-
No dead band in range	Act. Low Activation Point	0.0	-
	Act. High Activation Point	1.0	-
Insignificant hysteresis	Act. Hysteresis	0.0	-

Table 3: Coil Subsystem Characterising Parameters.

Model Parameter	**Value**	**Unit**
Face Area, Height	0.607	m
Face Area, Width	0.914	m
Number of Rows	6	-
Number of Circuits	18	-
Tube Internal Diameter	0.0125	m
Maximum Chilled Water Mass Flow Rate	1.6	Kg/s

Table 4: Design Intent Tolerances and Uncertainties.

Design Intent	**Model Parameter**	**Tol/Un**	**Unit**
Specified capacity	Tube Material Resistance	0.055	WK^{-1}
	Waterside Resistance Coeff.	0.122	$(rows)m^2s^{-0.8}W^{-1}m^{0.8}$
	Airside Resistance Coeff.	0.320	$(rows)m^2s^{-0.8}W^{-1}m^{0.8}$
	Total Heat Transfer	5.000	% (of kW load)
Nominally linear gain	Valve Authority	0.018	-
	Valve Curvature	0.500	-
No load when vlv. is closed	Valve Leakage	0.000	-
No dead band in range	Act. Low Activation Point	0.000	-
	Act. High Activation Point	0.000	-
Insignificant hysteresis	Act. Hysteresis	0.050	-
(As installed)	Face Area, Height	0.01	M
(As installed)	Face Area, Width	0.01	M
(As installed)	Number of Rows	0	-
(As installed)	Number of Circuits	0	-
(As installed)	Tube Internal Diameter	0.001	M
(As installed)	Max. Chilled Water Mass Flow Rate	0.198	kg/s

The coil resistance coefficients are derived from the ‘typical’ values published in Holmes (1982). The North American standard is ARI Standard 410 (2001) for rating cooling coils allows a -5% variation from the published performance. This percentage is implemented on the total heat transfer as estimated by the model. For ease of calculation it is implemented as ±5%. A nominally linear gain is desirable to allow good control of the process. The valve curvature characteristics and authority parameters determine the gain characteristics in combination with the coil model. A correctly balanced circuit will yield an authority, A, of $A = 0.5$. Consultation with HVAC practitioners suggests the balancing procedure is typically carried out to between ±5% and ±10% of the measured pressure drop. ±5% has been used as the design intent tolerance. For correctly balanced systems, it can be shown that the uncertainty in the authority due to this tolerance is $U_A = 0.018$. For a typical coil, if $A = 0.5$, reasonable linearity of the system gain can be generated for values of the valve curvature between $4.0 < \beta < 5.0$. The design intent tolerance in β is selected as $U_\beta = 0.5$.

There are no tolerances given for control port leakage or the restriction of the operating range. Although hysteresis in the system is undesirable, it is unreasonable, given HVAC grade equipment, to suggest that it should not be apparent in practice. Observations by the authors of a number of systems suggests that hysteresis at a level of 5% is not uncommon.

THE PERFORMANCE VALIDATION SCHEME AND TEST SYSTEM

The decision on whether the design intent has been realised in the target system is made by implementing the following rule,

IF $y - U_y < 0.0 < y + U_y$ *THEN the design intent has been realised.*

Where $y = Q_t^{'} - Q_t$. Q_t and $Q_t^{'}$ are the measured and predicted total heat transfer respectively. The scheme was applied to a full size test facility with a nominally rated 35kW cooling coil subsystem that formed part of a variable-air-volume air-handling unit serving test zones. Air volumetric flow rate measurements are available on the return air, V_{ra} (m^3/s), ambient, V_{aa}, and supply air, V_{sa}, paths. The relative humidity and temperature (local to the humidity sensors) measurements are available for the recirculated, H_{ra} (%) and T_{ra}, ambient, H_{aa} and T_{aa}, and supply air, H_{sa} and T_{sa}. The mixed air humidity, therefore has to be estimated from the ambient and return measurements. Water temperature entering, the coil was available. Finally, the primary circuit water mass flow rate, $\dot{m}_{w_{max}}$ (kg/s) was measured. The mass flow through the coil is not typically measured in HVAC systems. The part load mass flow rate is estimated using a valve/actuator model that has the cooling coil control signal, u_{cc}, as an input.

RESULTS

Observations are gathered from the target system by stepping the chilled water flow rate through the coil, from zero to maximum flow and back to zero, to account for hysteresis in the system. Figure 1 details the results of the performance validation tests. The top plots show the measured and predicted airside approach. The bottom plots show the prediction error and uncertainty. The plots are also split left to right showing the results for the tests as the value was opened, on the left, and closing on the right. The solid line indicates the design intent predicted by the model and the dotted line shows the actual system performance.

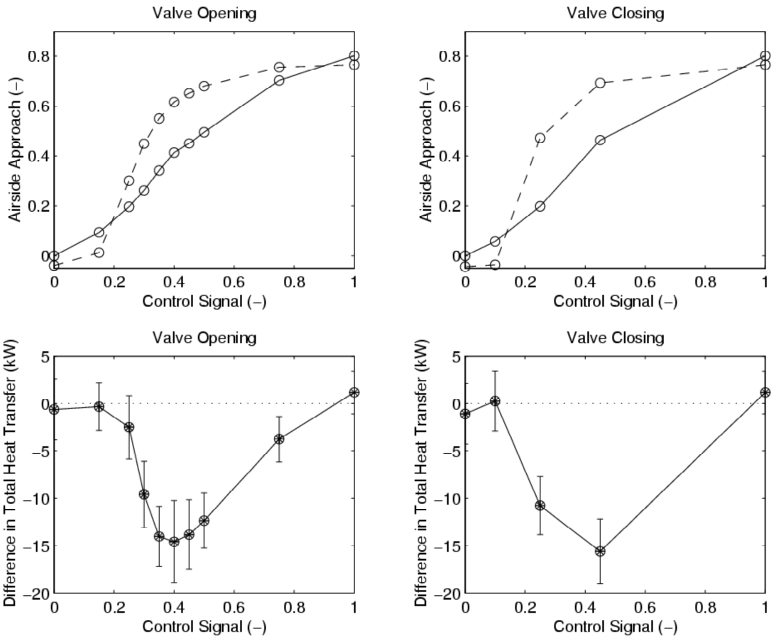

Figure 1: Test Results.

It is clear that the design intent has not been realised in this system and that the non-linearity in the system gain dominates. In relation to the design intent criteria set out earlier:

- there is no significant difference in full load capacity;
- the system gain is significantly non-linear;
- there is no significant difference in zero load capacity;
- restrictions in the operation range have no significant effect on the output;
- there appears to be an insignificant level of hysteresis.

The top plots clearly demonstrate that there is a dead band in the valve movement as it opens. The level of uncertainty present in the system, however, means that this does not significantly affect the system output. In this condition, the hysteresis is insignificant. A further study on the system revealed a ~10% difference between the flow rates when the actuator was opening to when it was closing, however, this was barely significant at the 95% level (Buswell, 2001), given the uncertainty in the measurements. On investigation, it appeared that the installed control valve had a linear characteristic and hence did not act to linearise the exponential coil characteristic.

CONCLUSIONS

A first principles model based performance validation scheme has been presented. The scheme uses uncertainty analysis to assimilate the measurement and model uncertainties and incorporate the uncertainty in the design intent to yield a single decision making threshold. A methodology for the scheme implementation is given and applied to a cooling coil subsystem installed in a real building.

Uncertainty in the measurements and in the model structure can be combined in a systematic manner to yield a transparent threshold. This is important when decisions have to be made based on initial observations. The framework of uncertainty analysis in conjunction with the use of first principles based models allows model parameters to represent aspects of the design intent. The design intent tolerances can be established from publications and best practice and applied to these parameters. This results in a single decision based on one threshold to determine whether the design intent has been realised in the installed system.

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