

NIST Technical Note 2037

**Measurement Uncertainty of the Air
System in the Intelligent Building
Agents Laboratory**

Dr. Amanda J. Pertzborn

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Abstract

The Intelligent Building Agents Laboratory (IBAL) has been designed and constructed to demonstrate the potential for distributed, intelligent software agents to perform optimization of control systems in commercial buildings. This technical note describes the collection of experimental data to assess time-dependent variability of instrumentation in the air system. This result is combined with other uncertainty components to yield a single value of uncertainty for each instrument used to characterize the operation and performance of the air system of the IBAL.

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Nomenclature

<i>a</i>	calibration constant
<i>f</i>	fan speed
<i>u</i>	uncertainty
AHU	air-handling unit
D	damper
EXF	exhaust fan
IBAL	Intelligent Building Agents Laboratory
OAU	outdoor air unit
V	valve
VAV	variable air volume
VFD	variable frequency drive
WSE	water side economizer
ZS	zone simulator

Subscripts

0	term in the calibration curve fit
1	level 1 result; term in the calibration curve

1. Introduction

The Intelligent Building Agents Laboratory (IBAL) is a testbed for the evaluation and design of intelligent control algorithms. The facility emulates a small commercial building and includes both an air system and a water (hydronic) system. Within the air system, cooling loads are generated by Zone Simulators (ZSs), which emulate the zones that exist in a real building and contain electric heating elements and steam spray humidifiers. Standard commercial air-conditioning equipment, including air-handling units (AHUs) and variable-air-volume units (VAVs), supply cooling air to the ZSs. The hydronic system consists of chillers, a water side economizer (WSE), and a thermal storage tank that produce cold propylene glycol for the cooling coils in the AHUs. Each pump and fan in the system is operated using a variable-frequency drive (VFD). The hydronic side of the system was fully described in TN1933 [1], and the air side was described in TN2025 [2]. The laboratory contains nearly 300 sensors and controlled devices.

Each sensor in the IBAL has a measurement uncertainty due to contributions from sources including calibration, data acquisition, and time-dependent effects. TN1933 and TN2025 discuss calibration and data acquisition uncertainty in detail. TN1970 [3] describes the method of assessing time-dependent effects and combining all the uncertainty components into a single value for each sensor in the hydronic system. This document addresses the time-dependent variability for the air system and how it is combined with the instrument uncertainty. Flow rate, pressure, and power consumption are the key values measured for the five fans, and position is the key value measured for the eleven damper and five steam valve actuators. Figure 1 shows the major components in the air system. OAU is the outdoor air unit and EXFs are the exhaust fans. The dampers are labeled with a D and valves are labeled with a V. The valves are used to modulate the flow rate of steam to the humidifiers. Figure 2 shows the locations of pressure and airflow measurements.

TN1970 presents the uncertainty calculation method in detail, so it will not be duplicated in this report. The final uncertainty applied to the measurements is, where relevant, a combination of: time-dependent variability, calibration uncertainty, uncertainty of the data acquisition system, and manufacturer-specified uncertainty, summed in quadrature. The calculations use a 95 % confidence interval [4]. The time-dependent variability is calculated from data collected from experiments run over multiple days. The change in the instrument reading from day to day is quantified as the time-dependent variability as described in TN1970; the next section describes the experiments used to collect the necessary data.

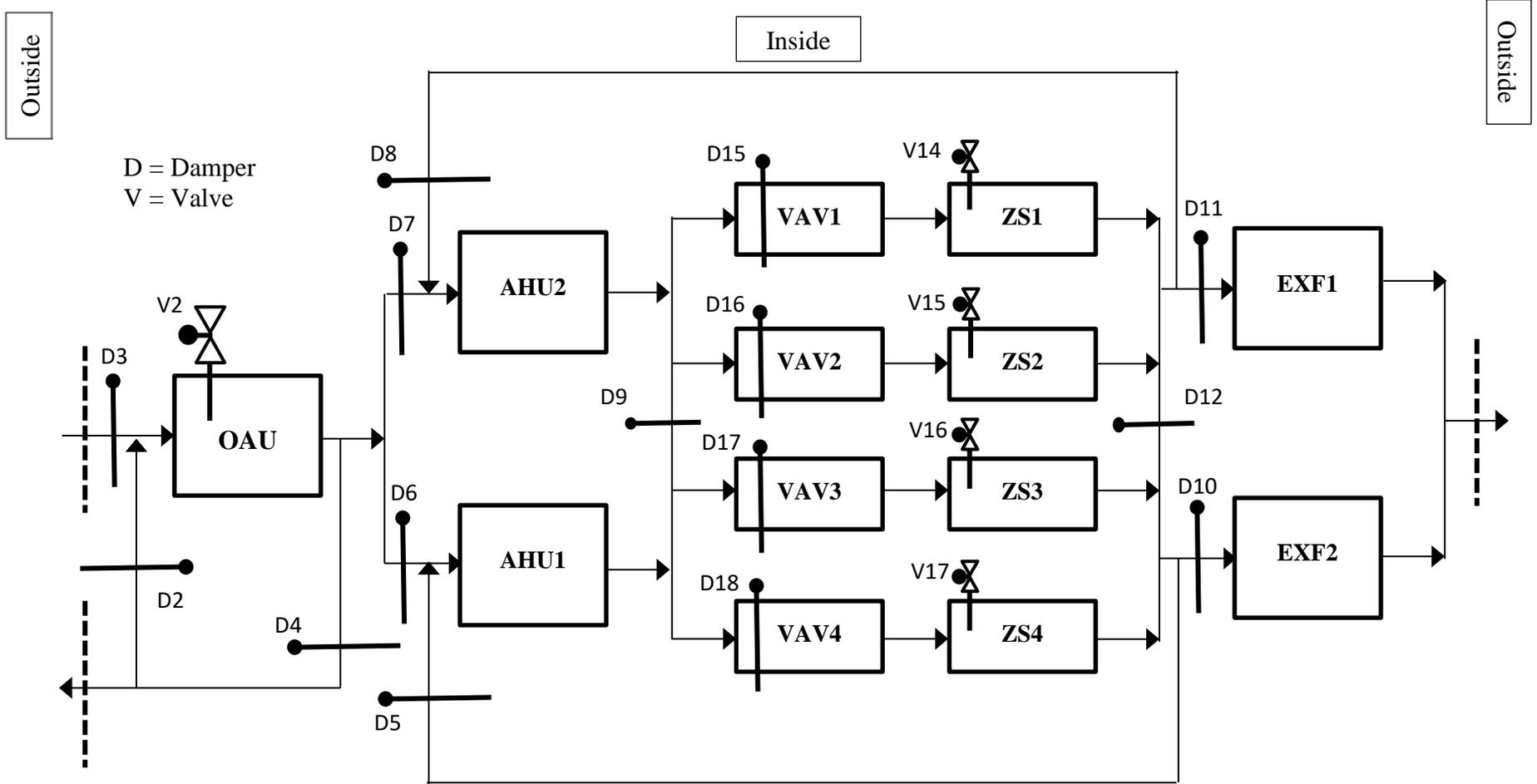


Figure 1. Schematic of the IBAL air system. The dashed lines indicate the exterior walls of the building.

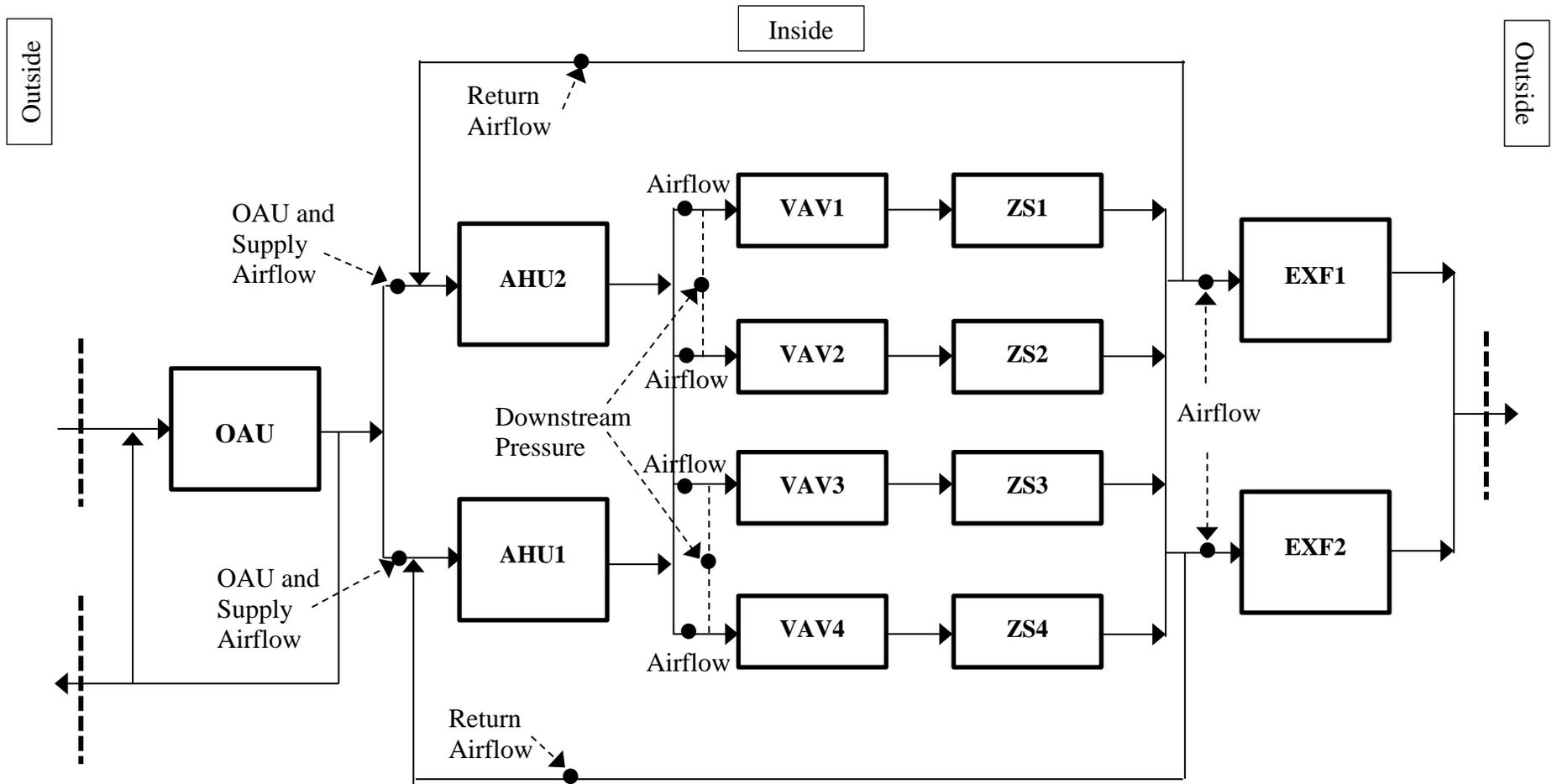


Figure 2. Schematic of the IBAL air system showing sensor positions. The dashed lines indicate the exterior walls of the building.

2. Experimental Design

This section contains a test matrix for each fan, damper, and valve in the air system. The test matrices were generated based on the anticipated system operating conditions, and the test results were used to calculate the time-dependent variability of each instrument. In all cases the fan speed is controlled by the VFD setting, which ranges from 0 Hz (no flow) to 60 Hz (maximum flow). The damper actuators in the main duct and VAVs operate based on a control voltage from (0 to 10) V and (2 to 10) V, respectively, and the valve actuators operate based on a control voltage from (2 to 10) V.

2.1. Fan Test Matrices

There are five fans in the system: OAU, AHU1, AHU2, EXF1, and EXF2. For each fan test the only variable is the fan speed; all other fan speeds and damper positions are held constant (Table 1). All valves were closed during the fan tests except for V2 during the OAU tests. The steam line was connected to the humidifier during these tests, so when V2 was open the fan had to be on prevent steam from condensing inside the unit. Tables 2 through 4 show the fan speeds for each day of testing for each fan. The order in which the fan speeds were applied was randomly selected. Each fan was tested independently of the others. For example, on Day 1 the four runs for the OAU test were conducted first, with each run lasting 15 minutes. All other fans were set to the speed indicated in Table 1. Then, the four runs for Day 1 of the AHU1 test were conducted, and so on.

Table 1. Settings of the system components when they are not under test.

Component	Setting
AHU1	60 Hz
AHU2	60 Hz
EXF1	30 Hz
EXF2	30 Hz
OAU	30 Hz
D2	Closed
D3	Open
D4	Open
D5	50 %
D6	50 %
D7	50 %
D8	50 %
D15	Open
D16	Open
D17	Open
D18	Open

Table 2. Test matrix for the OAU fan (fan speed [Hz]).

Run	Day 1	Day 2	Day 3	Day 4	Day 5
1	30	45	15	60	15
2	60	15	30	15	30
3	45	60	45	30	45
4	15	30	60	45	60

Table 3. Test matrix for the AHU (fan speed [Hz]).

Run	Day 1	Day 2	Day 3	Day 4	Day 5
1	30	60	60	15	45
2	45	15	30	30	30
3	60	45	15	45	60
4	15	30	45	60	15

Table 4. Test matrix for the EXF (fan speed [Hz]).

Run	Day 1	Day 2	Day 3	Day 4	Day 5
1	30	60	30	45	60
2	60	15	45	15	30
3	15	45	15	30	15
4	45	30	60	60	45

2.2. Damper and Valve Test Matrices

The repeatability and reproducibility of damper and valve position is assessed by randomly actuating the device multiple times on different days. Steam was actively entering V2 during the test runs, so the OAU fan and V2 were tested at the same time. Upstream steam valves were closed for V14, V15, V16, and V17, so those valve actuators, and all damper actuators, were tested with the fans off. Tables 5 through 10 show the test matrices for the damper and valve actuators.

Table 5. Test matrix for the damper actuators in the OAU (control signal [V]).

Run	Day 1			Day 2			Day 3			Day 4			Day 5		
	D2	D3	D4												
1	0	5.5	1.5	1.5	7.5	1.5	9.5	9.5	7.5	9.5	0	1.5	0	9.5	3.5
2	9.5	3.5	7.5	5.5	3.5	0	0	7.5	9.5	1.5	1.5	7.5	9.5	7.5	5.5
3	1.5	9.5	5.5	0	0	9.5	1.5	3.5	0	0	5.5	0	3.5	5.5	9.5
4	3.5	0	3.5	3.5	1.5	3.5	7.5	0	1.5	3.5	3.5	9.5	5.5	3.5	1.5
5	7.5	1.5	0	9.5	5.5	5.5	5.5	5.5	5.5	7.5	7.5	3.5	1.5	1.5	7.5
6	5.5	7.5	9.5	7.5	9.5	7.5	3.5	1.5	3.5	5.5	9.5	5.5	7.5	0	0

Table 6. Test matrix for V2, the valve actuator in the OAU (control signal [V]).

Run	Day 1	Day 2	Day 3	Day 4	Day 5
1	4	6	2	2	8
2	6	4	6	8	2
3	8	2	4	4	6
4	2	8	8	6	10
5	10	10	10	10	4

Table 7. Test matrix for the damper actuators in AHU1 (control signal [V]).

Run	Day 1		Day 2		Day 3		Day 4		Day 5	
	D5	D6								
1	1.5	5.5	9.5	0	0	3.5	9.5	1.5	0	7.5
2	7.5	1.5	3.5	5.5	1.5	0	7.5	5.5	7.5	3.5
3	3.5	9.5	1.5	9.5	5.5	9.5	0	3.5	5.5	0
4	0	7.5	0	3.5	7.5	7.5	3.5	0	3.5	1.5
5	5.5	0	5.5	1.5	9.5	5.5	5.5	7.5	1.5	5.5
6	9.5	3.5	7.5	7.5	3.5	1.5	1.5	9.5	9.5	9.5

Table 8. Test matrix for the damper actuators in AHU2 (control signal [V]).

Run	Day 1		Day 2		Day 3		Day 4		Day 5	
	D7	D8								
1	5.5	7.5	9.5	1.5	0	5.5	3.5	3.5	3.5	5.5
2	0	5.5	7.5	5.5	1.5	9.5	5.5	0	0	0
3	1.5	9.5	0	3.5	3.5	1.5	7.5	9.5	1.5	1.5
4	7.5	1.5	5.5	7.5	5.5	7.5	9.5	5.5	9.5	3.5
5	3.5	3.5	1.5	9.5	9.5	0	0	1.5	5.5	7.5
6	9.5	0	3.5	0	7.5	3.5	1.5	7.5	7.5	9.5

Table 9. Test matrix for damper actuators in the VAVs (control signal [V]).

Run	Day 1				Day 2				Day 3				Day 4				Day 5			
	D15	D16	D17	D18																
1	10	2	6	6	10	2	8	2	10	4	4	6	4	2	2	8	8	10	4	8
2	2	6	10	2	4	10	4	6	4	8	8	10	8	8	4	6	2	2	6	10
3	8	8	2	8	8	6	2	4	8	6	2	4	2	6	10	2	10	8	8	4
4	6	4	8	4	6	8	6	10	6	10	6	2	6	10	8	10	6	6	2	6
5	4	10	4	10	2	4	10	8	2	2	10	8	10	4	6	4	4	4	10	2

Table 10. Test matrix for valve actuators in the ZSs (control signal [V]).

Run	Day 1				Day 2				Day 3				Day 4				Day 5			
	V14	V15	V16	V17																
1	4	10	4	8	8	6	8	6	8	2	10	6	10	2	10	6	2	2	4	2
2	2	4	8	6	6	10	2	10	6	10	2	10	8	6	8	8	4	4	6	10
3	10	8	10	4	10	2	6	2	10	8	6	8	2	4	2	4	8	8	10	8
4	6	6	2	2	4	8	4	4	2	6	8	4	6	8	6	10	6	10	8	6
5	8	2	6	10	2	4	10	8	4	4	4	2	4	10	4	2	10	6	2	4

2.3. Complete Test Plan

For every test, data were collected on five different days. For each fan the individual run of each test lasted at least 15 minutes, and for each valve and damper actuator the individual run of each test lasted at least 7 minutes. These timeframes were selected so that the system had time to reach steady state and then acquire at least 20 data points (sample rate of 0.1 Hz).

3. Results

This section presents the uncertainty results for the fans, dampers, and valves. The figures present the mean results and the absolute and relative uncertainties.

3.1. Fans

Figures 3 through 7 show the mean airflow, power, and pressure as a function of fan speed for each fan. Error bars are included on each data point, though in some cases they are too small to be seen. For the AHUs, the return airflow has an unusual shape, exhibiting a minimum somewhere near the middle of the power range. For AHU1, the airflow dips to near zero at 30 Hz and for AHU2 the airflow dips to its lowest point at 45 Hz. The reason for this behavior is the combined fan curve of the AHU and the EXF associated with that AHU, as well as the system pressure. For example, when the AHU1 and EXF2 fans operate at 30 Hz, there is no return airflow. This means that the airflow from the AHU1 fan is the same as the airflow from the EXF2 fan. Return flow results from the AHU generating more airflow than the EXF. The point at which the two fans balance (30 Hz in this case) will vary based on the position of the dampers, which will change the system pressure and the operating point on the combined fan curve.

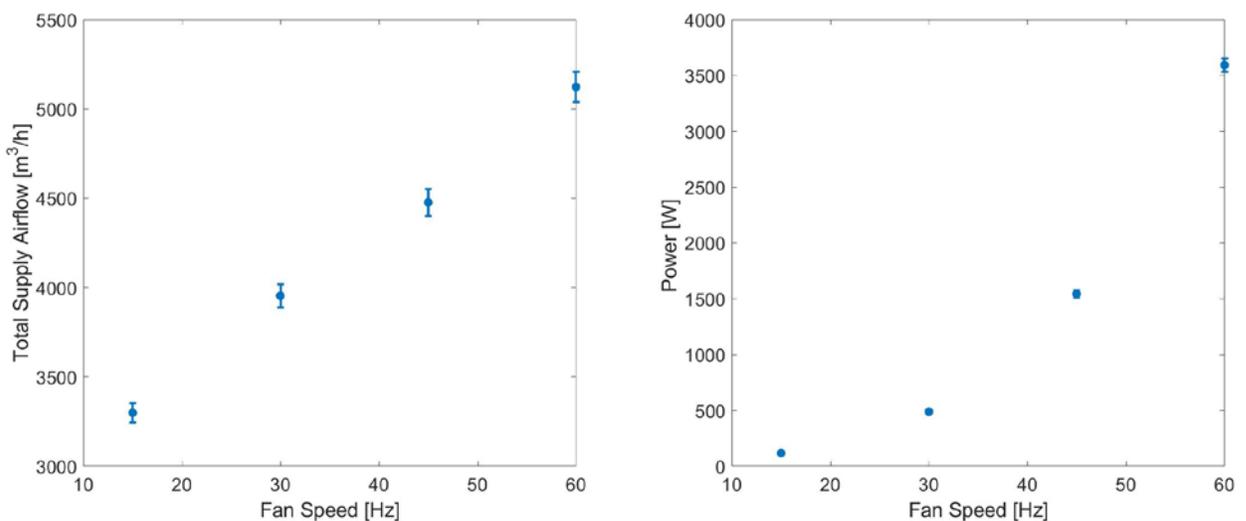


Figure 3. Airflow and power results for the OAU fan.

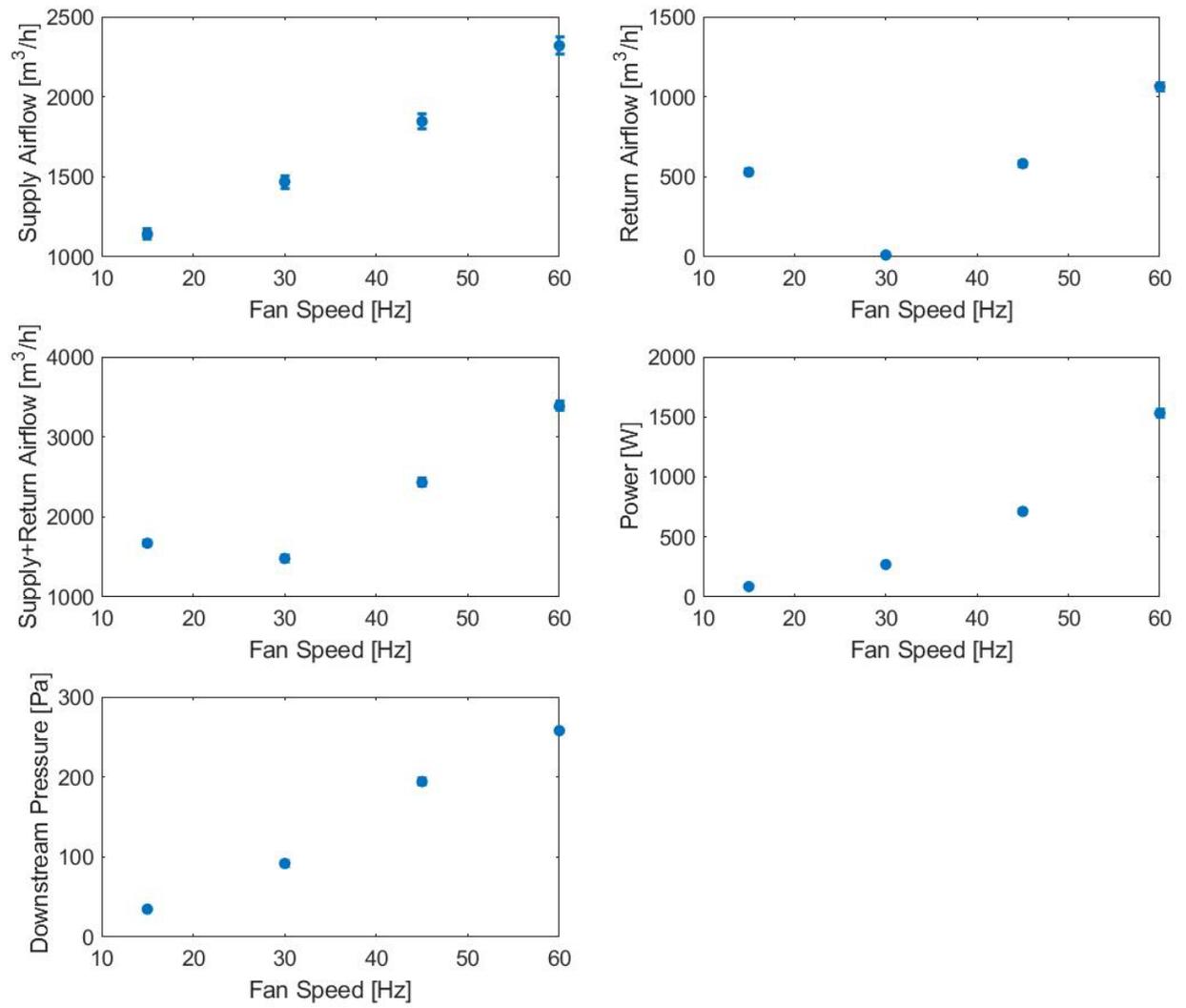


Figure 4. Airflow, power, and pressure results for the AHU1 fan. Supply + Return Airflow is the sum of the separate supply and return measurements.

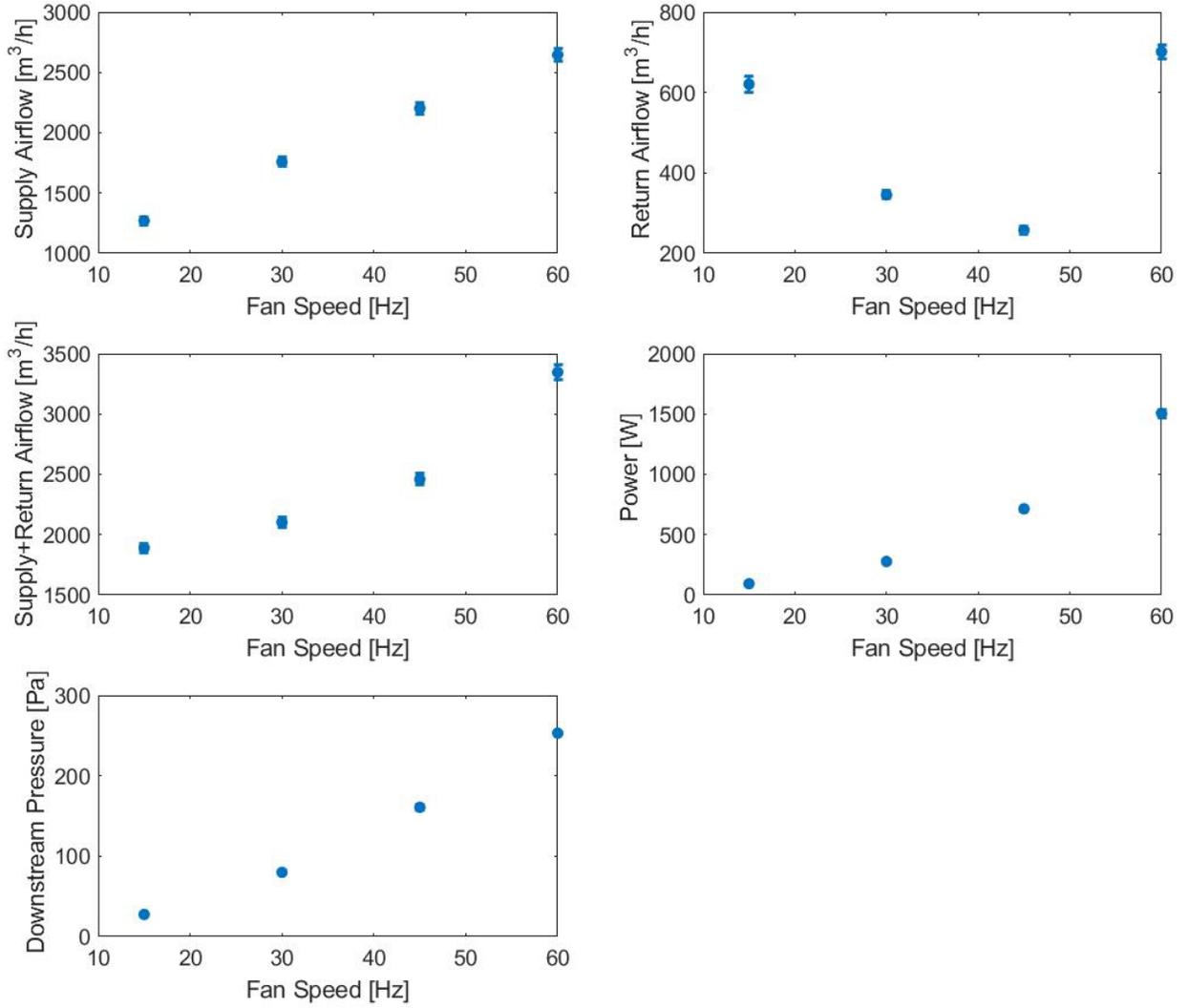


Figure 5. Airflow, power, and pressure results for the AHU2 fan. Supply + Return Airflow is the sum of the separate supply and return measurements.

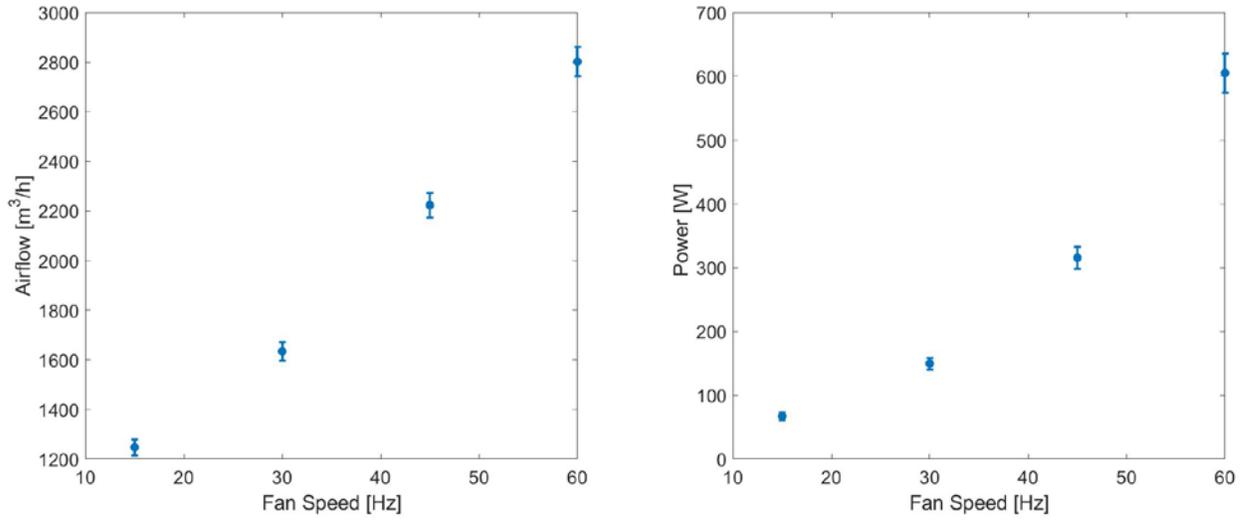


Figure 6. Airflow and power results for the EXF1 fan.

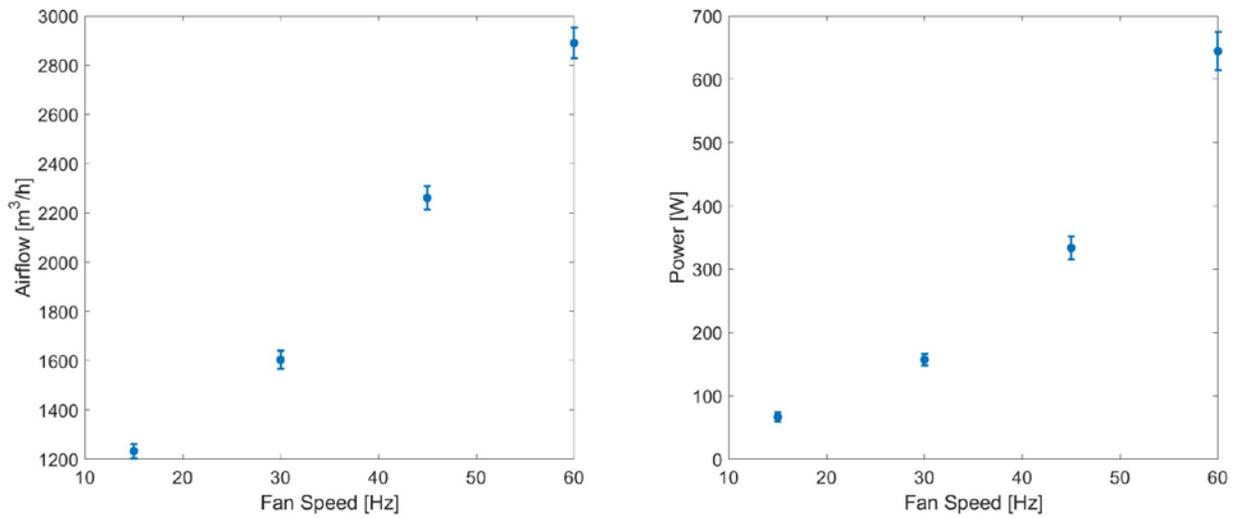


Figure 7. Airflow and power results for the EXF2 fan.

Figures 8 through 12 show the total uncertainty for the fan measurements. When the relative uncertainty is greater than 10 %, it is because the value of the measurement is near zero and therefore the absolute uncertainty is divided by a very small number.

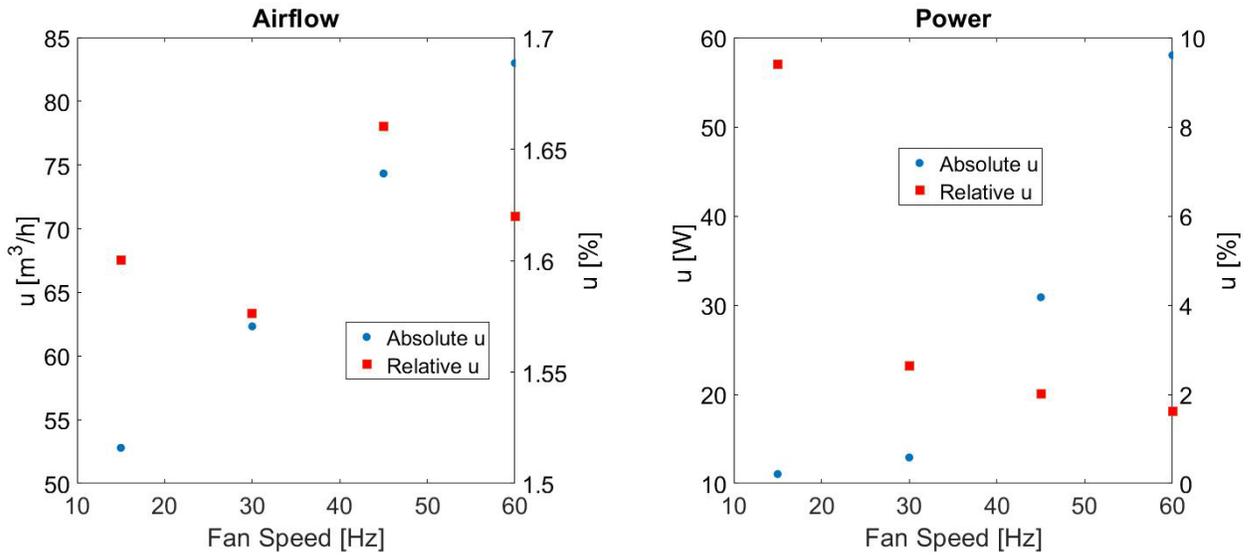


Figure 8. Total uncertainty of measurements related to the OAU fan.

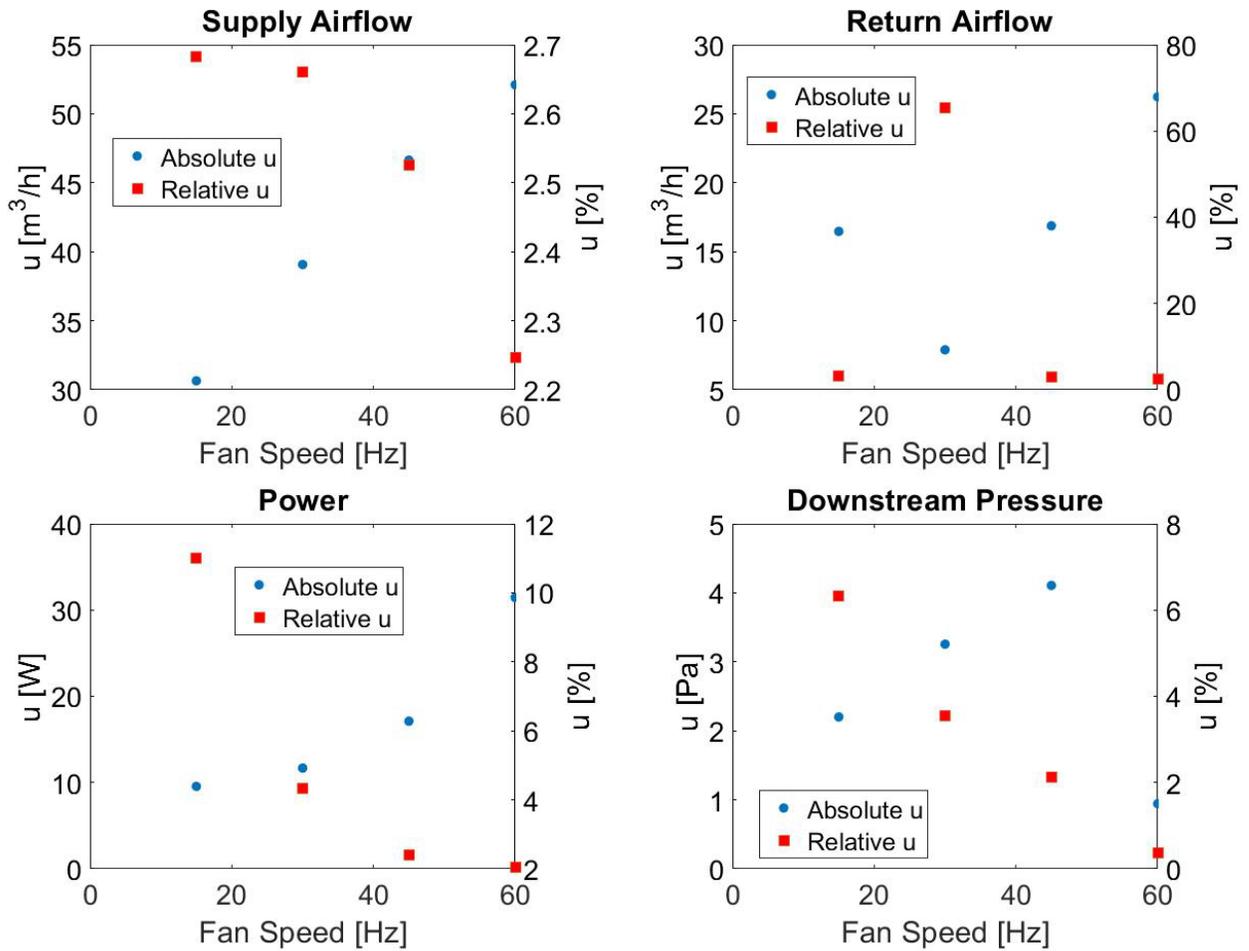


Figure 9. Total uncertainty of measurements related to the AHU1 fan.

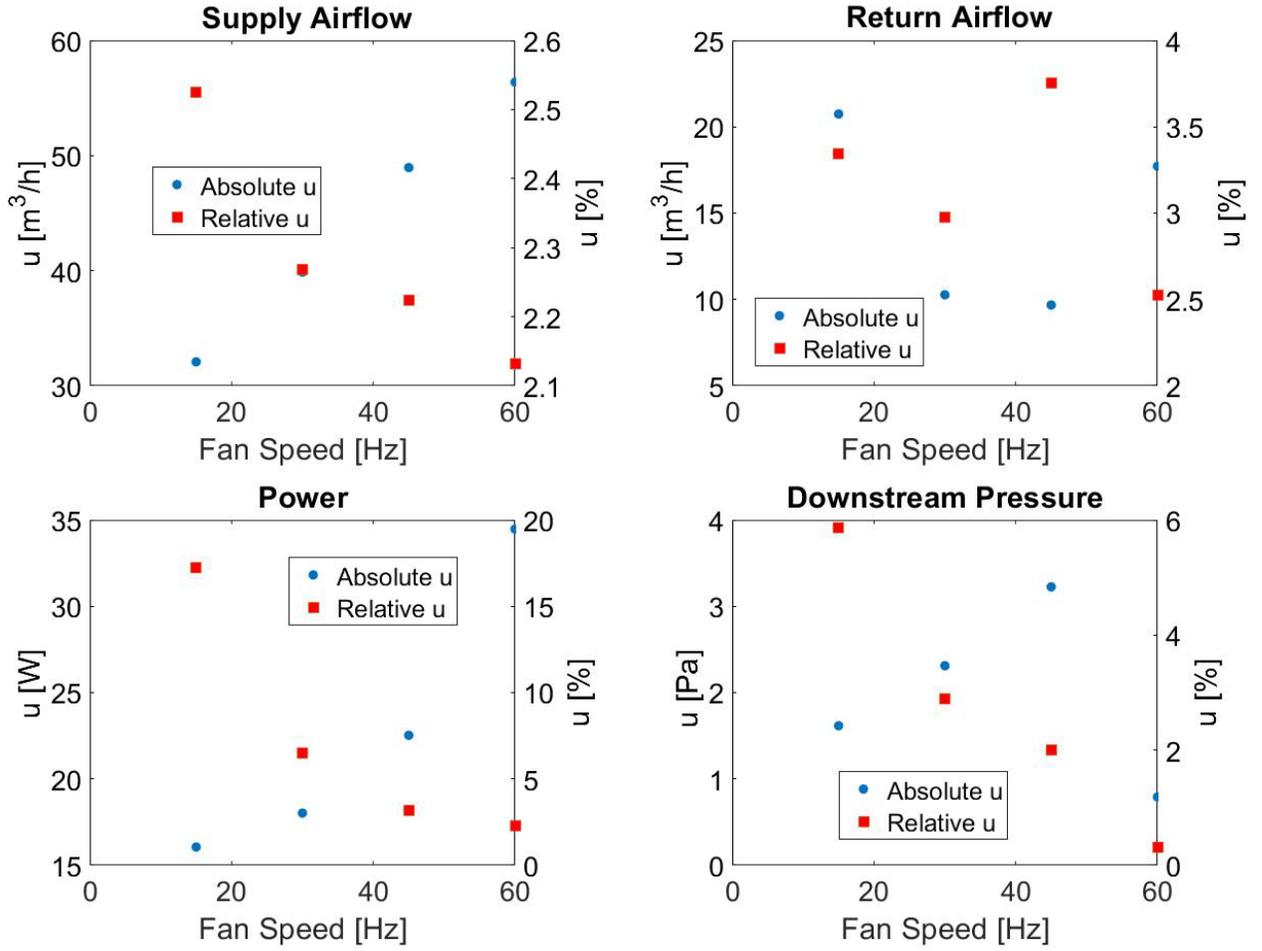


Figure 10. Total uncertainty of measurements related to the AHU2 fan.

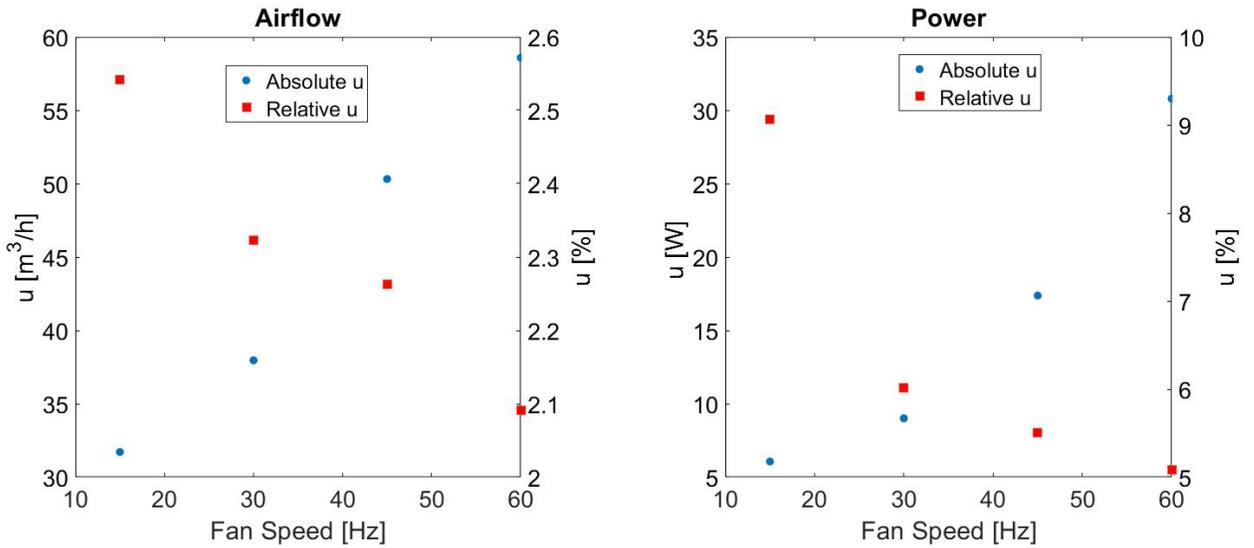


Figure 11. Total uncertainty of measurements related to the EXF1 fan.

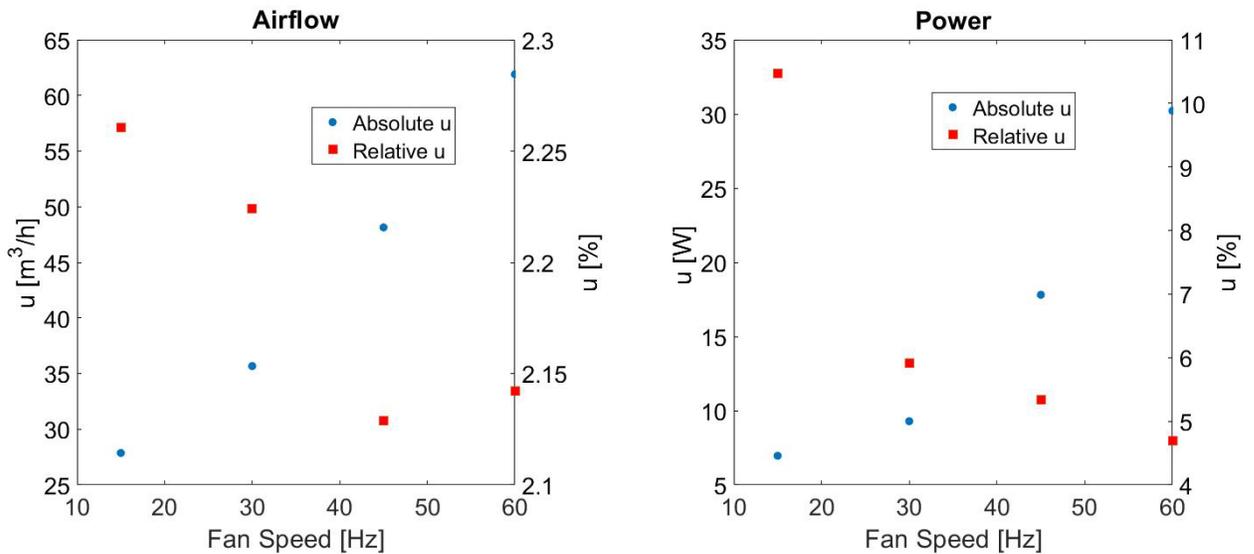


Figure 12. Total uncertainty of measurements related to the EXF2 fan.

Figure 8 through Figure 12 show that for all but the return airflow measurements (Figures 9 and 10), the uncertainty is a function of the fan speed. As such, the uncertainty for each measurement is calculated from a fit to the uncertainty curves as a function of fan speed [Hz], f :

$$\begin{aligned}
 \text{Airflow, Pressure: } u &= a_0 + a_1 f \\
 \text{Power: } \frac{1}{u} &= a_0 + a_1 f
 \end{aligned}
 \tag{1}$$

For the return airflow, which does not display a consistent trend, the uncertainty is based on the maximum of the measured uncertainties. The coefficients for each curve (see Eq. 1) and the R^2 value of the curve fit are given in Table 11. The Channel column is the data acquisition channel number assigned to the measurement and S/N is the serial number of the instrument.

Table 11. Summary of uncertainty results for the fans.

Fan	Measurement	Channel	S/N	a_0	a_1	R^2
OAU	Airflow [m ³ /h]	326+327	707 957, 708 382	42.5	0.684	0.99
	Power ⁻¹ [W ⁻¹]	493	14 090 243	0.121	-0.00176	0.92
AHU1	Supply Airflow [m ³ /h]	326	707 957	24.1	0.480	0.99
	Return Airflow [m ³ /h]	325	708 439	26.2		
	Power ⁻¹ [W ⁻¹]	59	14 090 238	0.132	-0.00164	0.99
	Pressure [Pa]	5		1.28	0.064	0.99
AHU2	Supply Airflow [m ³ /h]	327	708 382	23.8	0.547	1.00
	Return Airflow [m ³ /h]	334	708 329	20.7		
	Power ⁻¹ [W ⁻¹]	60	14 090 246	0.0755	-0.00074	0.96
	Pressure [Pa]	9		0.78	0.054	0.99
EXF1	Airflow [m ³ /h]	306	708 432	21.4	0.620	0.98
	Power ⁻¹ [W ⁻¹]	18	14 090 235	0.204	-0.0030	0.96
EXF2	Airflow [m ³ /h]	307	708 422	14.7	0.764	0.98
	Power ⁻¹ [W ⁻¹]	72	14 090 236	0.181	-0.00255	0.97

For the airflow measurements, the manufacturer uncertainty dominates over the time-dependent variability, but for the other measurements the time-dependent variability is dominant. The Appendix contains tables with these data.

3.2. Dampers and Valves

For the dampers and valves, the variability of the feedback signal is assumed to be a reasonable proxy for the damper/valve position, which may be important when that signal is used by the control system to determine or set the current or future damper/valve position. Figures 14 through 17 show the feedback signal (position) versus the control signal for each device. Error bars are included in the plots, though in general they are so small that they are not visible. D2, D3, D6, and D7 do not operate across their full theoretical range of voltages. For example, when D7 (Figure 15) receives a control signal of 9.5 V, the feedback signal is approximately 7.7 V instead of 9.5 V, which is only slightly greater than the feedback when the control signal is 7.5 V.

There are a couple of possible causes for this mismatch: 1) the two signals should match but the actuator is not working correctly; 2) there is a mismatch between the linkage on the damper and the actuator (e.g., the damper fully opens/closes before the actuator has moved through its full range). The actuator for D6 was removed and the damper was manually opened and closed to determine if the damper was operating over its full physical range.

When the damper was fully open, the feedback signal was still well below 9.5 V, supporting the latter explanation.

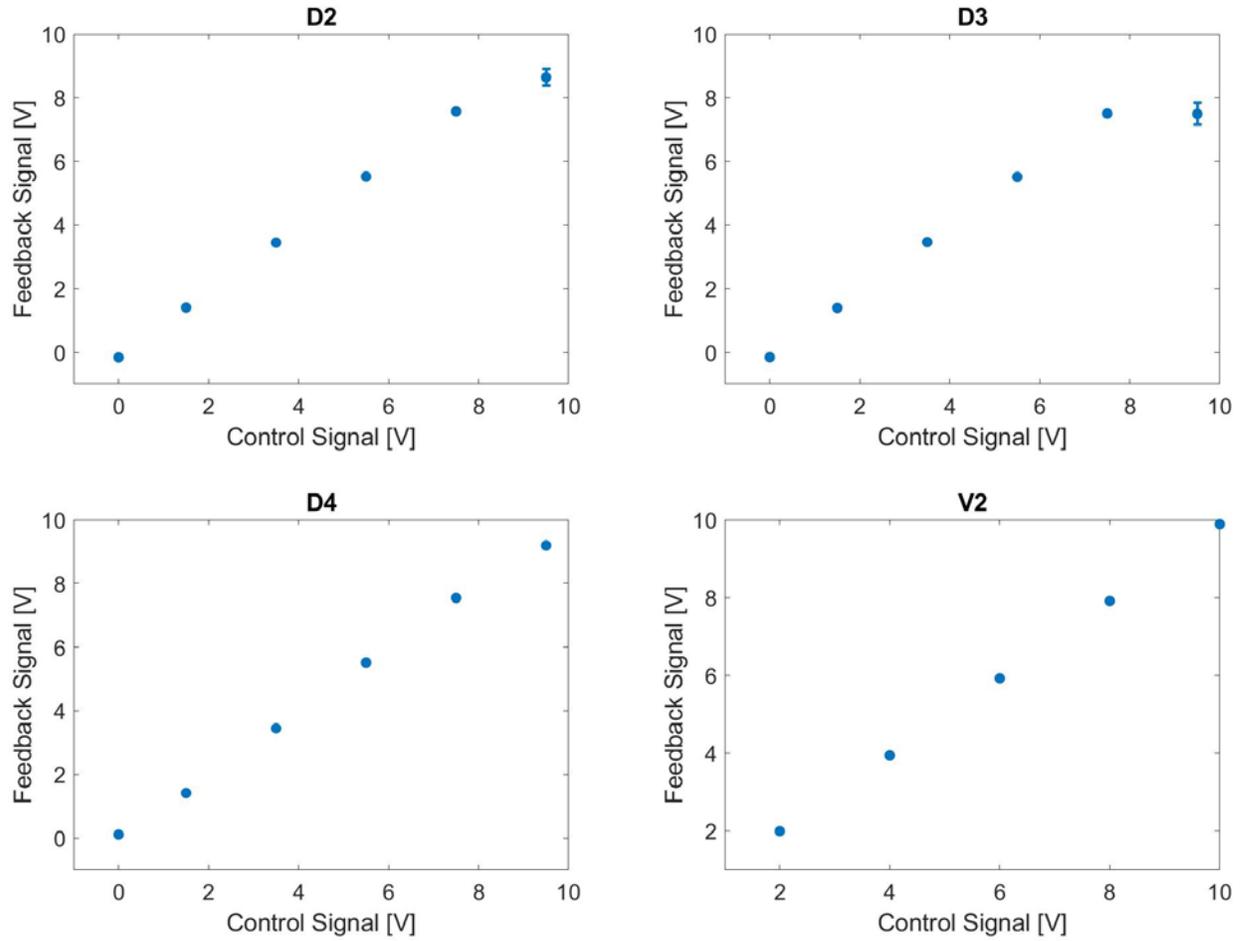


Figure 13. Results for the OAU damper and valve actuators.

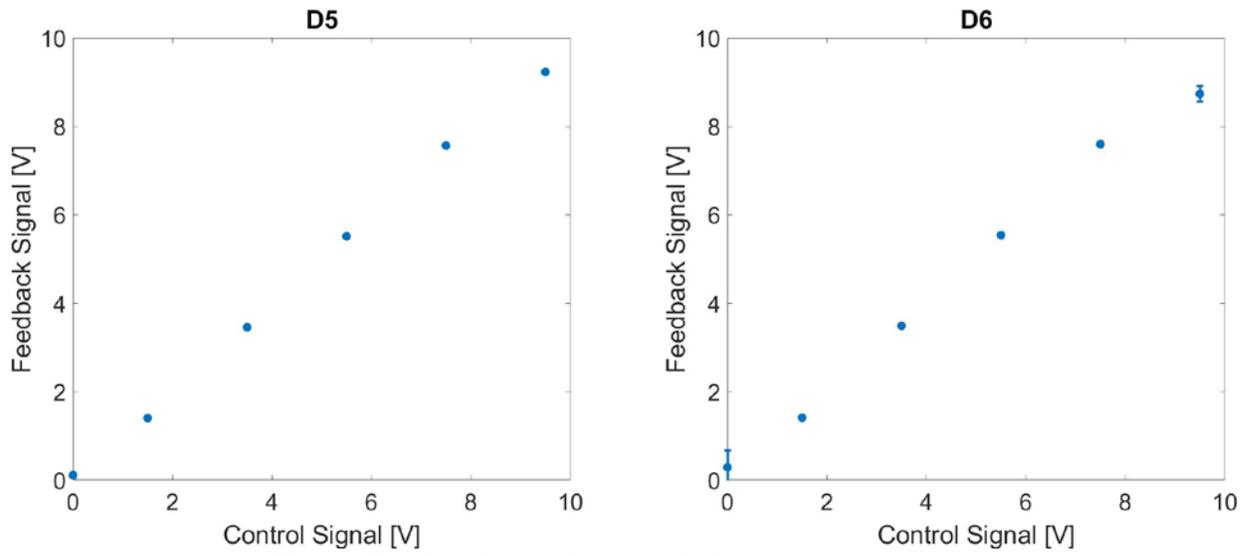


Figure 14. Results for the AHU1 damper actuators.

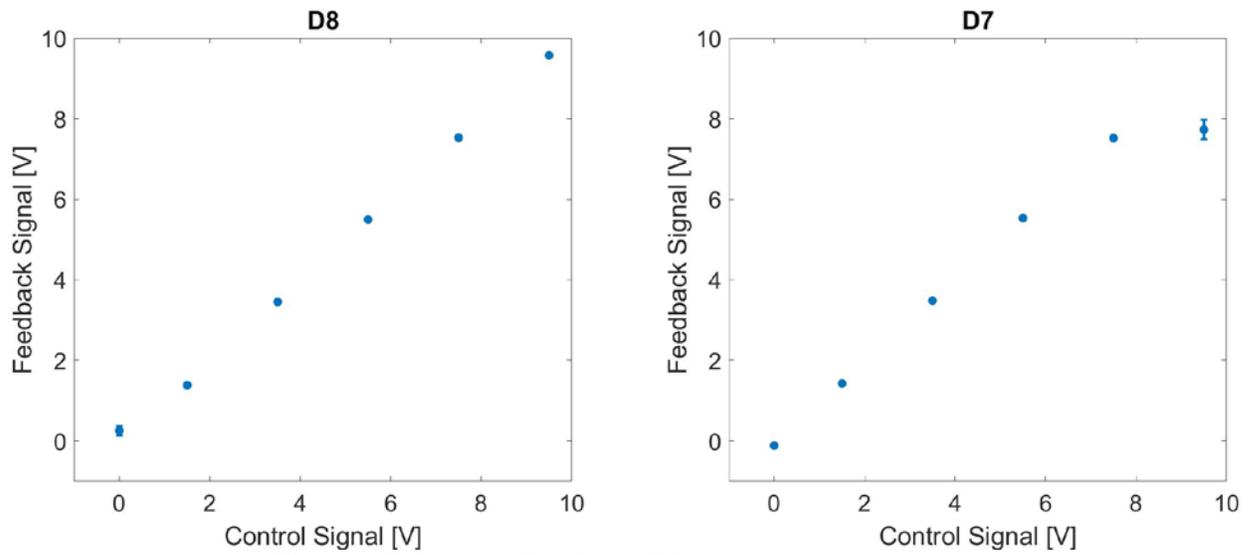


Figure 15. Results for the AHU2 damper actuators.

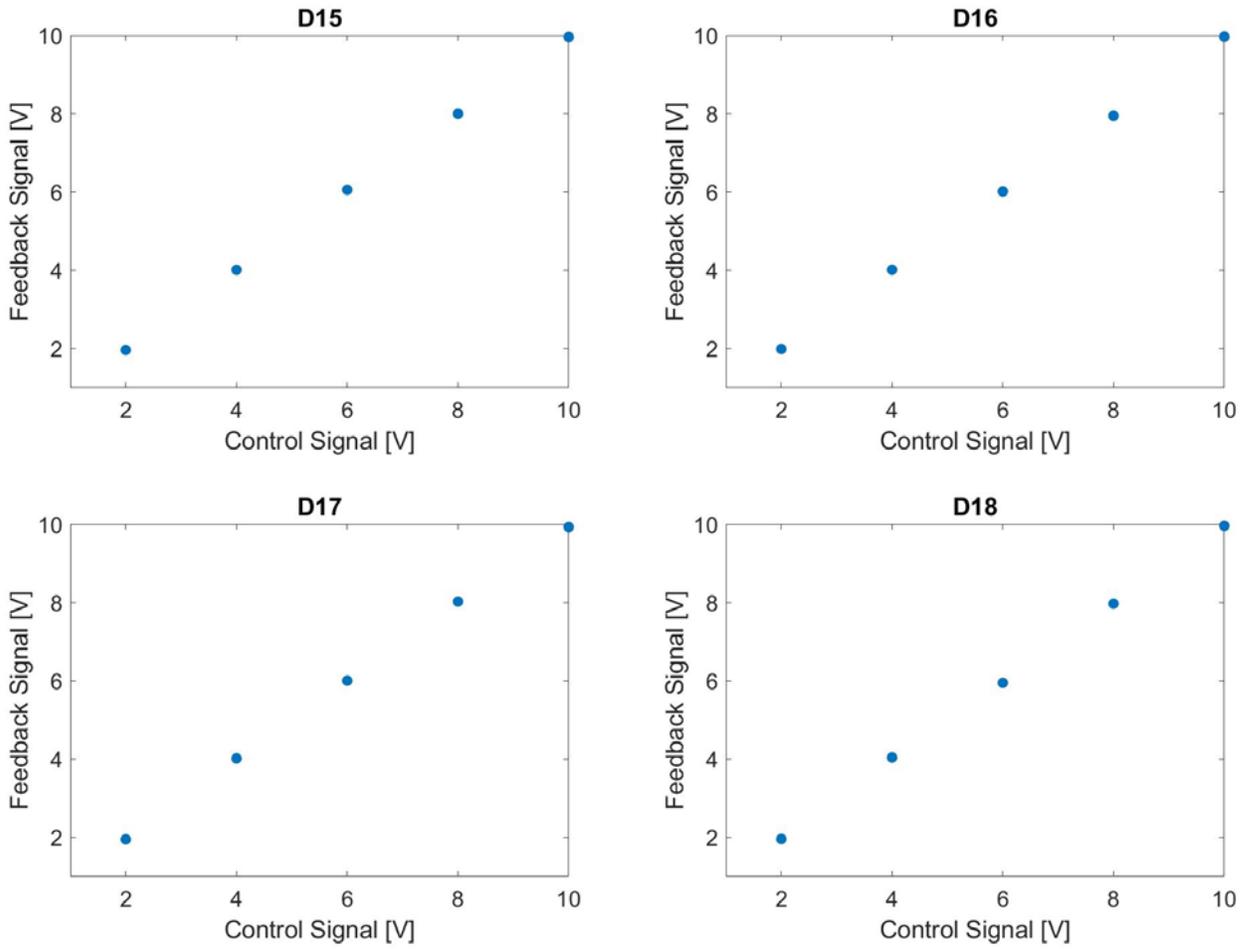


Figure 16. Results for the VAV damper actuators.

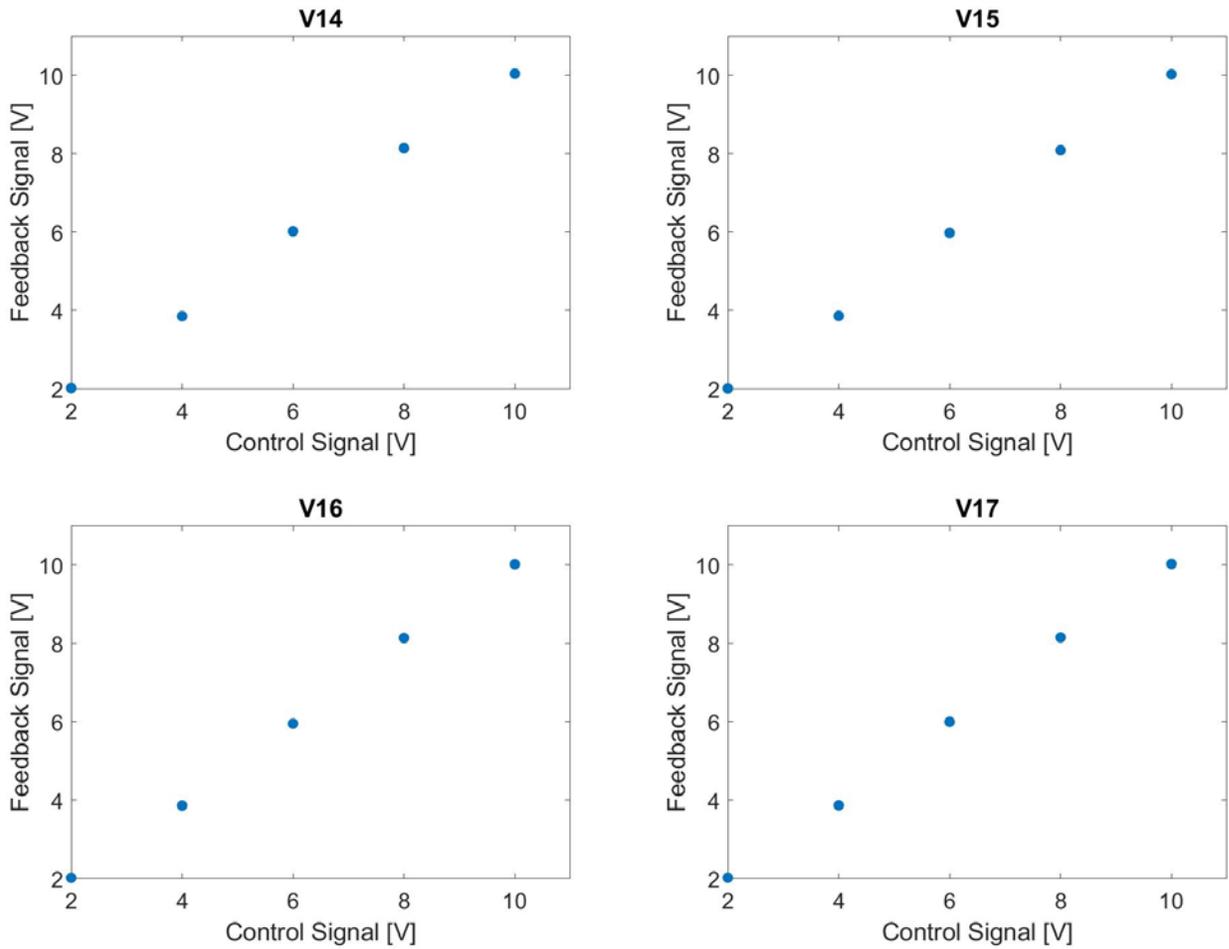


Figure 17. Results for the ZS steam valve actuators.

Figures 19 through 22 show the total uncertainty for each damper and valve actuator (see TN1970 for a full explanation of total uncertainty). In general, the uncertainty is less than 0.1 V, but in a few cases the uncertainty is larger. The relative uncertainty is generally less than 5 %; where the relative uncertainty was large, it was excluded from the figure (see the Appendix for the full data set). There are two reasons for the large uncertainties. First, when the damper position is near zero the uncertainty is divided by a small number, which can cause the relative uncertainty to be large. Second, some dampers display a large range of feedback values at the fully open position. D2, D3, D6, and D7 were mentioned earlier because the damper does not operate across the actuator’s full range, and, as shown in Table 12, those dampers have greater uncertainty at the upper range of control signals. In addition, D6 and D8 have greater uncertainty at the low end of their range. The time-dependent variability dominates the uncertainty calculation (see the Appendix for data tables).

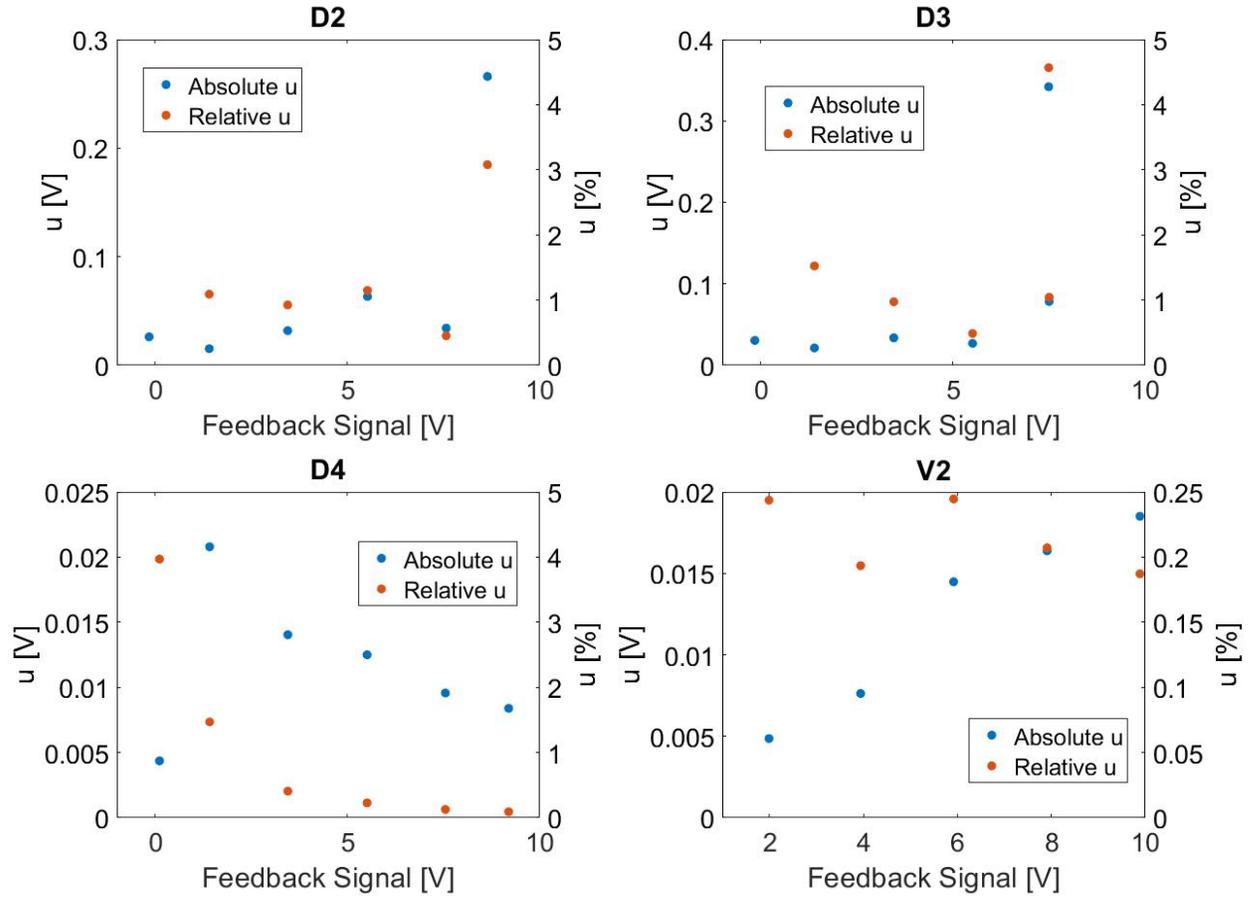


Figure 18. Total uncertainty of the damper and valve actuators in OAU.

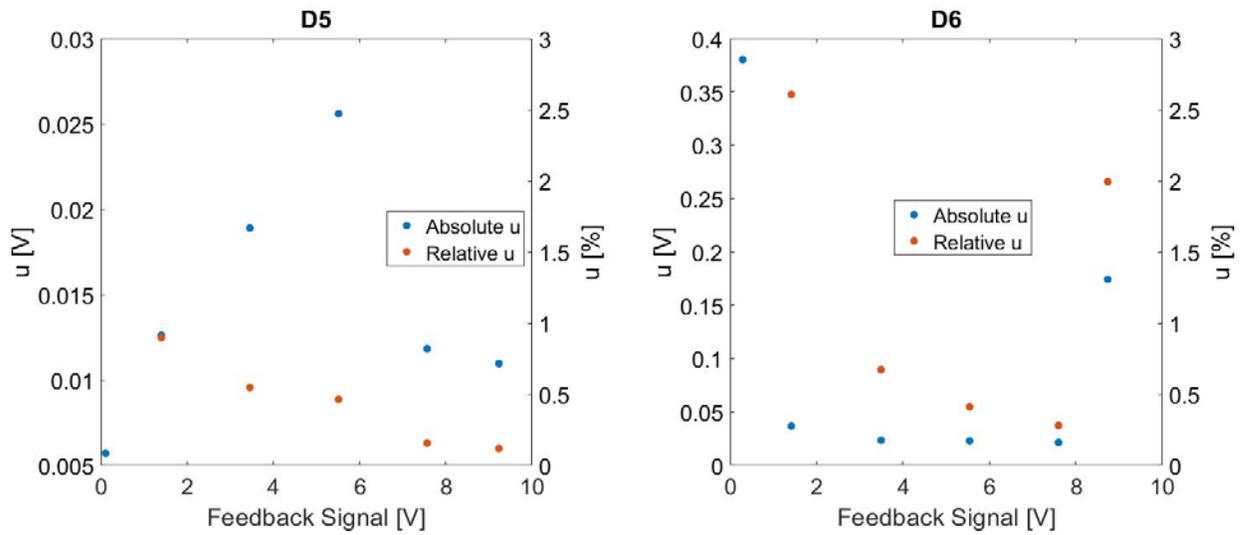


Figure 19. Total uncertainty for the damper actuators in AHU1.

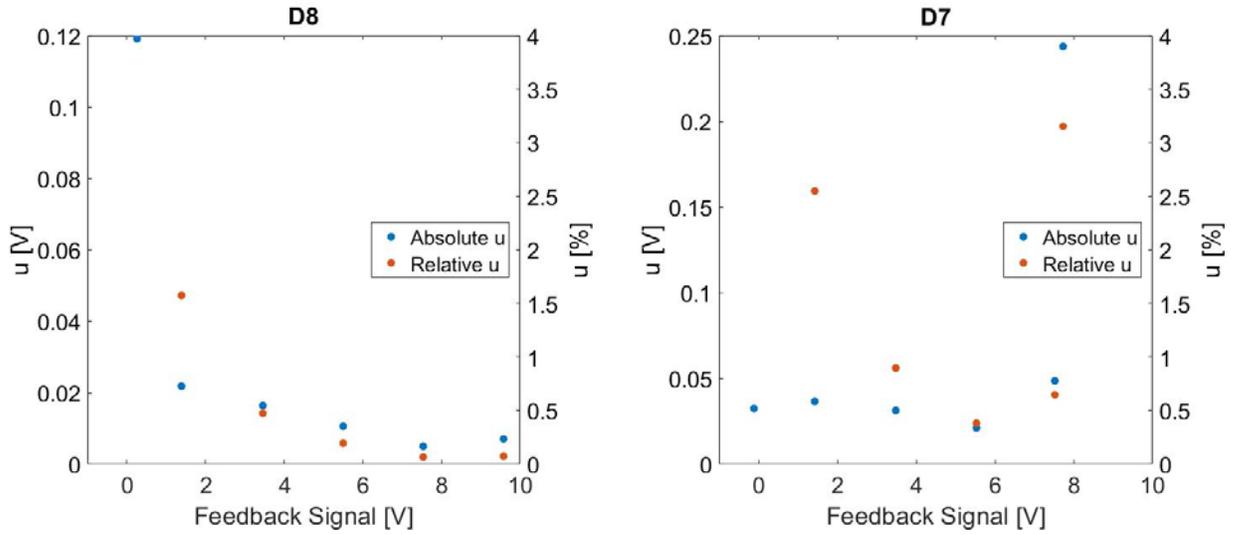


Figure 20. Total uncertainty for the damper actuators in AHU2.

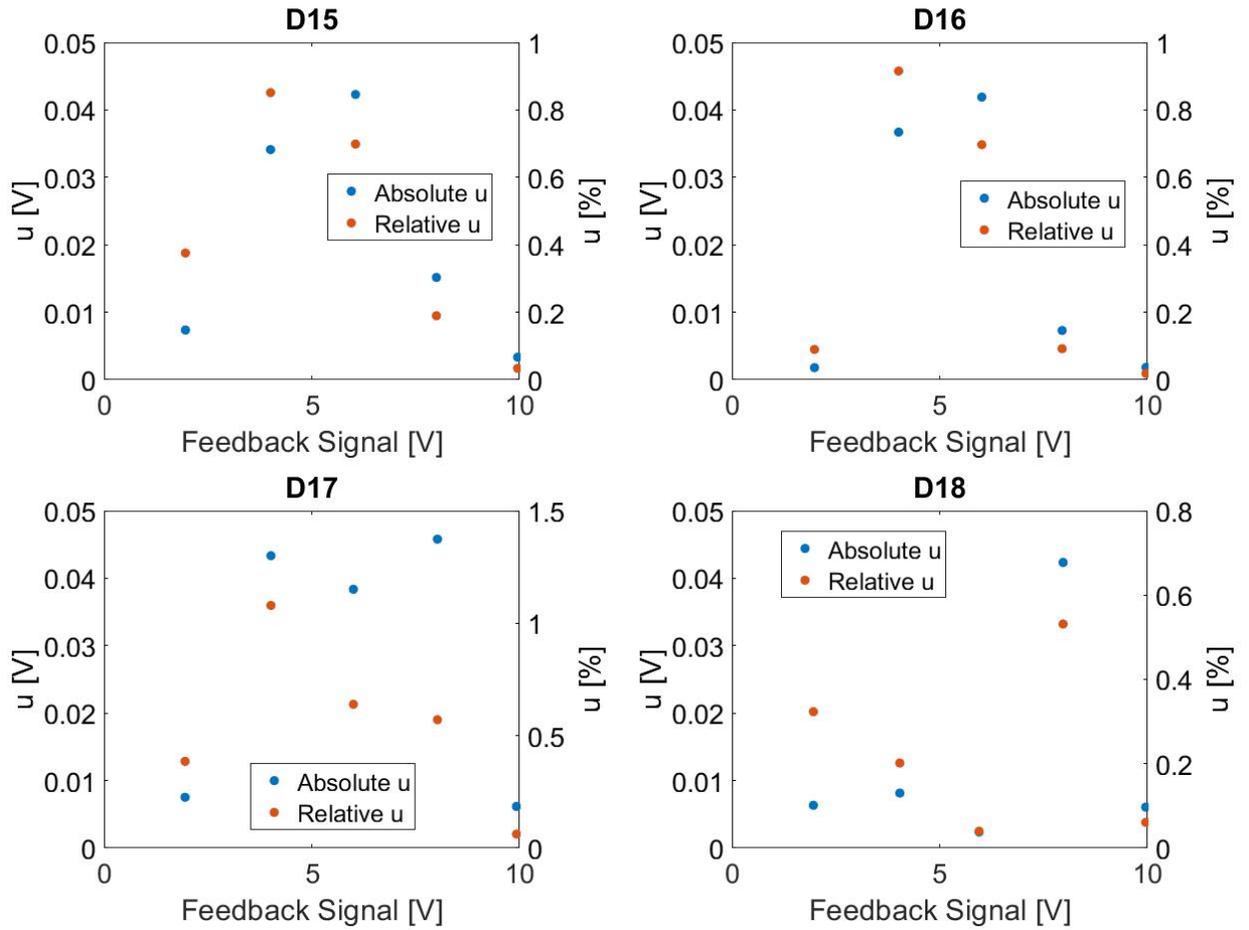


Figure 21. Total uncertainty for the damper actuators in the VAVs.

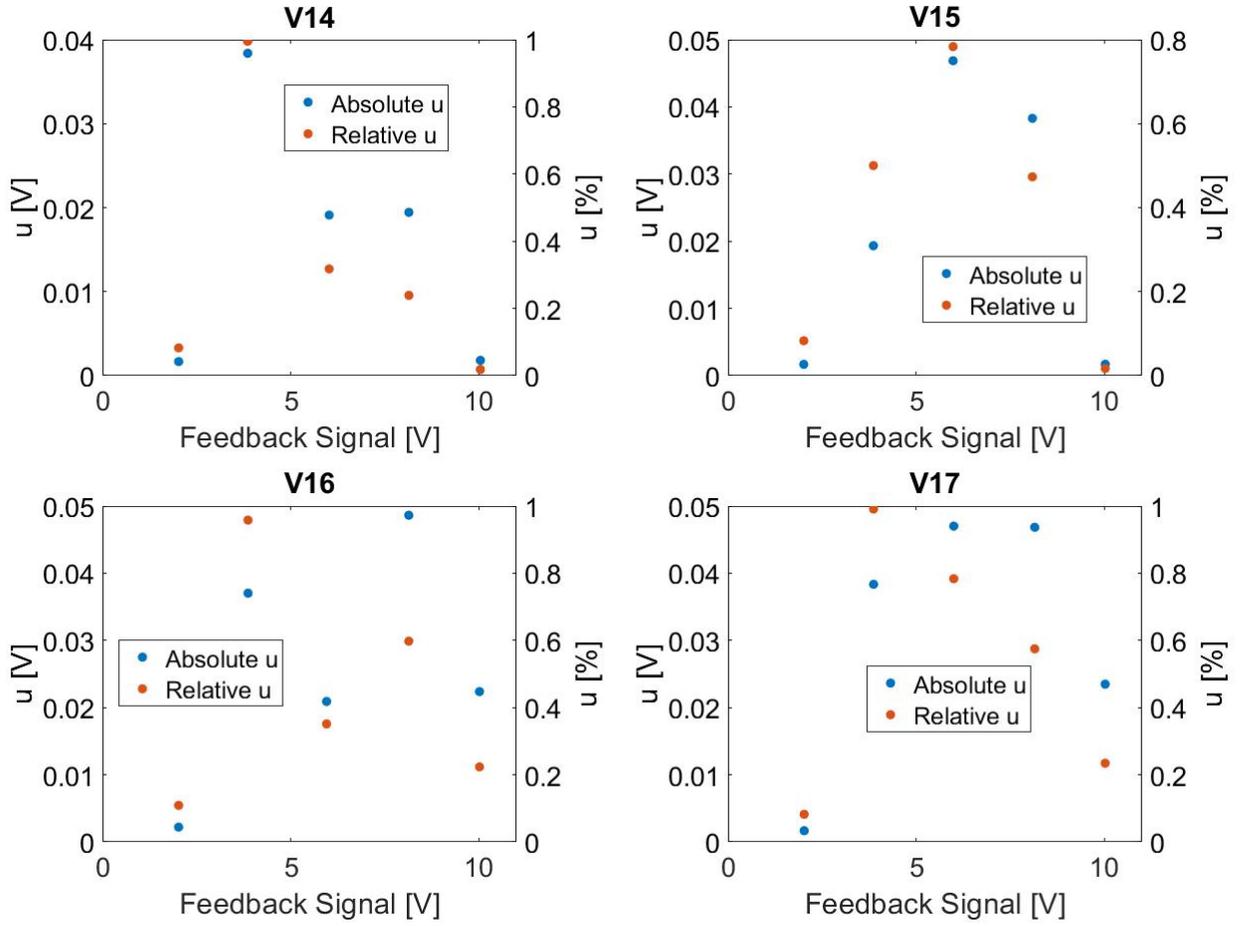


Figure 22. Total uncertainty for the valve actuators in the ZSs.

Table 12. Uncertainties for the damper and valve actuators.

Device	Channel Number	Actuator Part Number	Uncertainty [V]		
			$\leq 1.5 \text{ V}$	$1.5 \text{ V} < V \leq 9 \text{ V}$	$> 9 \text{ V}$
D2	304	GMA161.1P	0.063		0.27
D3	305	GMA161.1P	0.078		0.34
D4	309	GMA161.1P	0.021		
V2	359	NVF24-MFT-E US	0.019		
D5	310	GMA161.1P	0.026		
D6	329	GMA161.1P	0.38	0.037	0.17
D8	335	GMA161.1P	0.12	0.022	
D7	328	GMA161.1P	0.049		0.24
D15	336	LMB24-SR-T	0.042		
D16	360	LMB24-SR-T	0.042		
D17	363	LMB24-SR-T	0.042		
D18	364	LMB24-SR-T	0.042		
V14	385	MS51-7103-100	0.038		
V15	386	MS51-7103-100	0.047		
V16	387	MS51-7103-100	0.049		
V17	388	MS51-7103-100	0.047		

4. Summary

This report presented the total measurement uncertainty of instruments in the air system associated with fans and the actuators for dampers and steam valves. Those calculations included the time-dependent variability of these devices. The results of this analysis will be used in reporting the uncertainty of measurements in the IBAL in future publications. Now that the uncertainties have been established, the strength of the conclusions drawn from experiments in the IBAL can be determined.

5. References

- [1] A. J. Pertzborn, "NIST Technical Note 1933: Intelligent Building Agents Laboratory : Hydronic System Design," 2016.
- [2] A. J. Pertzborn and D. A. Veronica, "NIST Technical Note 2025: Intelligent Building Agents Laboratory : Air System Design," 2018.
- [3] A. J. Pertzborn, "NIST Technical Note 1970: Measurement Uncertainty in the Hydronic System in the IBAL," 2017.
- [4] NIST, "NIST/SEMATECH e-Handbook of Statistical Methods," 2013. [Online]. Available: <https://www.itl.nist.gov/div898/handbook/>. [Accessed: 06-Sep-2018].

6. Appendix: Uncertainty Data

Tables 13 through 33 contain the full uncertainty data from Figures 8 through 12 and 18 through 22. Tables 34 through 43 show the ratio of time-dependent variability to the instrument and manufacturer uncertainty:

$$\sqrt{\frac{(\text{time} - \text{dependent})^2}{[(\text{instrument})^2 + (\text{manufacturer})^2]}}$$

Table 13 Uncertainty results for the instruments related to the OAU fan.

Control Signal [Hz]	Airflow		Power	
	u [m ³ /h]	u [%]	u [W]	u [%]
15	52.8	1.60	11.1	9.40
30	62.3	1.58	12.9	2.64
45	74.3	1.66	30.9	2.00
60	83.0	1.62	58.0	1.61

Table 14 Uncertainty results for the instruments related to the AHU1 fan.

Control Signal [Hz]	Supply Airflow		Return Airflow		Power		Downstream Pressure	
	u [m ³ /h]	u [%]	u [m ³ /h]	u [%]	u [W]	u [%]	u [Pa]	u [%]
15	30.6	2.68	16.5	3.11	9.6	11.01	2.5	80.2
30	39.1	2.66	7.9	65.4	11.7	4.32	3.0	6.65
45	46.6	2.53	16.9	2.90	17.1	2.40	2.9	2.62
60	52.1	2.25	26.2	2.46	31.5	2.06	1.8	1.40

Table 15 Uncertainty results for the instruments related to the AHU2 fan.

Control Signal [Hz]	Supply Airflow		Return Airflow		Power		Downstream Pressure	
	u [m ³ /h]	u [%]	u [m ³ /h]	u [%]	u [W]	u [%]	u [Pa]	u [%]
15	32.1	2.53	20.7	3.34	16.1	17.22	1.3	988.2
30	39.9	2.27	10.3	3.0	18.0	6.50	2.2	5.21
45	49.0	2.22	9.7	3.75	22.5	3.15	2.3	2.08
60	56.4	2.13	17.7	2.53	34.5	2.29	1.3	1.00

Table 16 Uncertainty results for the instruments related to the EXF1 fan.

Control Signal [Hz]	Airflow		Power	
	u [m ³ /h]	u [%]	u [W]	u [%]
15	31.7	2.54	6.1	9.06
30	38.0	2.32	9.0	6.02
45	50.3	2.26	17.4	5.51
60	58.6	2.09	30.8	5.09

Table 17 Uncertainty results for the instruments related to the EXF2 fan.

Control Signal [Hz]	Airflow		Power	
	u [m ³ /h]	u [%]	u [W]	u [%]
15	27.9	2.26	7.0	10.47
30	35.7	2.22	9.3	5.91
45	48.1	2.13	17.8	5.34
60	61.9	2.14	30.2	4.69

Table 18 Uncertainty results for the D2 actuator.

Control Signal [V]	Feedback Signal [V]	u [V]	u [%]
0	-0.16	0.026	-16.3
1.5	1.40	0.015	1.09
3.5	3.44	0.032	0.93
5.5	5.52	0.063	1.15
7.5	7.57	0.034	0.45
9.5	8.64	0.266	3.08

Table 19 Uncertainty results for the D3 actuator.

Control Signal [V]	Feedback Signal [V]	u [V]	u [%]
0	-0.15	0.031	-19.8
1.5	1.39	0.021	1.52
3.5	3.46	0.034	0.97
5.5	5.51	0.027	0.49
7.5	7.50	0.078	1.04
9.5	7.49	0.342	4.57

Table 20 Uncertainty results for the D4 actuator.

Control Signal [V]	Feedback Signal [V]	u [V]	u [%]
0	0.11	0.004	3.97
1.5	1.41	0.021	1.47
3.5	3.45	0.014	0.41
5.5	5.51	0.013	0.23
7.5	7.54	0.010	0.13
9.5	9.19	0.008	0.09

Table 21 Uncertainty results for the D5 actuator.

Control Signal [V]	Feedback Signal [V]	u [V]	u [%]
0	0.11	0.006	5.06
1.5	1.40	0.013	0.90
3.5	3.46	0.019	0.55
5.5	5.51	0.026	0.46
7.5	7.57	0.012	0.16
9.5	9.23	0.011	0.12

Table 22 Uncertainty results for the D6 actuator.

Control Signal [V]	Feedback Signal [V]	u [V]	u [%]
0	0.29	0.381	130.4
1.5	1.42	0.037	2.61
3.5	3.49	0.023	0.67
5.5	5.54	0.023	0.41
7.5	7.60	0.021	0.28
9.5	8.74	0.174	1.99

Table 23 Uncertainty results for the D7 actuator.

Control Signal [V]	Feedback Signal [V]	u [V]	u [%]
0	-0.11	0.032	-28.8
1.5	1.43	0.036	2.55
3.5	3.49	0.031	0.89
5.5	5.53	0.021	0.38
7.5	7.52	0.049	0.65
9.5	7.73	0.244	3.15

Table 24 Uncertainty results for the D8 actuator.

Control Signal [V]	Feedback Signal [V]	u [V]	u [%]
0	0.26	0.119	46.1
1.5	1.39	0.022	1.57
3.5	3.46	0.016	0.47
5.5	5.50	0.011	0.19
7.5	7.53	0.005	0.07
9.5	9.58	0.007	0.07

Table 25 Uncertainty results for the D15 actuator.

Control Signal [V]	Feedback Signal [V]	u [V]	u [%]
2	1.96	0.007	0.38
4	4.01	0.034	0.85
6	6.05	0.042	0.70
8	8.00	0.015	0.19
10	9.95	0.003	0.03

Table 26 Uncertainty results for the D16 actuator.

Control Signal [V]	Feedback Signal [V]	u [V]	u [%]
2	1.99	0.002	0.09
4	4.01	0.037	0.92
6	6.01	0.042	0.70
8	7.94	0.007	0.09
10	9.96	0.002	0.02

Table 27 Uncertainty results for the D17 actuator.

Control Signal [V]	Feedback Signal [V]	u [V]	u [%]
2	1.95	0.008	0.39
4	4.02	0.043	1.08
6	6.00	0.038	0.64
8	8.02	0.046	0.57
10	9.93	0.006	0.06

Table 28 Uncertainty results for the D18 actuator.

Control Signal [V]	Feedback Signal [V]	u [V]	u [%]
2	1.96	0.006	0.32
4	4.04	0.008	0.20
6	5.95	0.002	0.04
8	7.97	0.042	0.53
10	9.96	0.006	0.06

Table 29 Uncertainty results for the V2 actuator.

Control Signal [V]	Feedback Signal [V]	u [V]	u [%]
2	1.99	0.005	0.24
4	3.94	0.008	0.19
6	5.92	0.014	0.24
8	7.91	0.016	0.21
10	9.89	0.019	0.19

Table 30 Uncertainty results for the V14 actuator.

Control Signal [V]	Feedback Signal [V]	u [V]	u [%]
2	2.02	0.002	0.08
4	3.86	0.038	1.00
6	6.02	0.019	0.32
8	8.14	0.019	0.24
10	10.04	0.002	0.02

Table 31 Uncertainty results for the V15 actuator.

Control Signal [V]	Feedback Signal [V]	u [V]	u [%]
2	2.01	0.002	0.08
4	3.86	0.019	0.50
6	5.98	0.047	0.78
8	8.09	0.038	0.47
10	10.02	0.002	0.02

Table 32 Uncertainty results for the V16 actuator.

Control Signal [V]	Feedback Signal [V]	u [V]	u [%]
2	2.02	0.002	0.11
4	3.86	0.037	0.96
6	5.95	0.021	0.35
8	8.14	0.049	0.60
10	10.02	0.022	0.22

Table 33 Uncertainty results for the V17 actuator.

Control Signal [V]	Feedback Signal [V]	u [V]	u [%]
2	2.02	0.002	0.08
4	3.87	0.038	0.99
6	6.00	0.047	0.78
8	8.15	0.047	0.57
10	10.02	0.023	0.23

Table 34 Time-dependent variability versus instrument and manufacturer uncertainty for the instruments associated with the OAU fan.

Control Signal [V]	Airflow	Power
15	0.46	14.51
30	0.45	16.96
45	0.59	40.62
60	0.53	76.34

Table 35 Time-dependent variability versus instrument and manufacturer uncertainty for the instruments associated with the AHU1 fan.

Control Signal [V]	Supply Airflow	Return Airflow	Power	Downstream Pressure
15	0.81	1.08	3.74	2.14
30	0.82	1.89	4.62	3.35
45	0.74	0.95	6.86	4.30
60	0.48	0.69	12.69	0.17

Table 36 Time-dependent variability versus instrument and manufacturer uncertainty for the instruments associated with the AHU2 fan.

Control Signal [V]	Supply Airflow	Return Airflow	Power	Downstream Pressure
15	0.70	1.25	6.42	1.78
30	0.49	0.85	7.23	2.75
45	0.45	1.15	9.07	3.96
60	0.34	0.70	13.92	0.03

Table 37 Time-dependent variability versus instrument and manufacturer uncertainty for the instruments associated with the EXF1 fan.

Control Signal [V]	Airflow	Power
15	0.76	2.24
30	0.58	3.51
45	0.52	6.96
60	0.30	12.43

Table 38 Time-dependent variability versus instrument and manufacturer uncertainty for the instruments associated with the EXF2 fan.

Control Signal [V]	Airflow	Power
15	0.50	2.63
30	0.47	3.63
45	0.35	7.14
60	0.38	12.19

Table 39 Time-dependent variability versus instrument uncertainty for the damper actuators in the OAU.

Control Signal [V]	D2	D3	D4
0	15.8	18.4	2.4
1.5	9.2	12.8	12.5
3.5	19.2	20.3	8.4
5.5	38.1	16.2	7.5
7.5	20.6	47.2	5.7
9.5	160.2	206.0	5.0

Table 40 Time-dependent variability versus instrument uncertainty for the damper actuators in AHU1.

Control Signal [V]	D5	D6
0	3.3	229.2
1.5	7.5	22.2
3.5	11.3	14.1
5.5	15.4	13.7
7.5	7.1	12.8
9.5	6.5	105.0

Table 41 Time-dependent variability versus instrument uncertainty for the damper actuators in AHU2.

Control Signal [V]	D8	D7
0	71.8	19.4
1.5	13.1	21.9
3.5	9.8	18.8
5.5	6.3	12.7
7.5	2.8	29.2
9.5	4.1	146.8

Table 42 Time-dependent variability versus instrument uncertainty for the damper actuators in the VAVs.

Control Signal [V]	D15	D16	D17	D18
2	4.3	0.4	4.4	3.7
4	20.5	22.1	26.1	4.8
6	25.5	25.2	23.1	1.0
8	9.1	4.3	27.6	25.5
10	1.7	0.5	3.6	3.5

Table 43 Time-dependent variability versus instrument uncertainty for the steam valve actuators.

Control Signal [V]	V2	V14	V15	V16	V17
2	2.8	0.1	0.1	0.9	0.1
4	4.5	23.1	11.6	22.3	23.1
6	8.7	11.5	28.2	12.6	28.3
8	9.8	11.7	23.0	29.3	28.2
10	11.1	0.4	0.2	13.4	14.1