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# Calibration Procedure in Control Systems for Heating, Ventilating and Air Conditioning Systems: Prediction

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*Abstract*— **Performance prediction is applicable to electric, electronic, and pneumatic type automatic temperature control (ATC) systems. Performance prediction is the process of calculating what the output of the controller should be, based on the conditions being sensed and controlled. Performance prediction is one step in the overall calibration procedure. In this paper, we challenges on performance prediction for control systems in HVAC systems that contains predicting resistance, predicting output voltage, predicting output Pressure, inaccuracies in pneumatic and electronic measuring instruments.**

*Index Terms*— **performance prediction, automatic temperature control, HVAC system.**

## I. Introduction

Performance prediction is applicable to electric, electronic, and pneumatic type automatic temperature control (ATC) systems. Performance prediction is the process of calculating what the output of the controller should be, based on the conditions being sensed and controlled. Performance prediction is one step in the overall calibration procedure. Calibration is the overall process of making the measured output agrees with the predicted output. The four steps in the calibration process are:

1- Predict
2- Measure
3- Verify
4- Adjust

First, *predict* the output value at the current sensed media conditions by use of defined calculations. Next, *measure* the actual output value and the current conditions of the sensed media. Then, *verify* calibration of the controller by comparing the measured output value with the predicted output value. Finally, if the measured output value does not agree with the predicted output value, *adjust* the controller calibration mechanism until the measured value does agree with the predicted value. When the predicted value agrees with the measured value for the same sensed media conditions, the controller is said to be "in calibration"[1,2].

In this paper, we challenges on performance prediction for control systems in HVAC systems that contains predicting electronic sensor resistance, predicting electronic controller output voltage, predicting dual-input electronic controller output voltage, predicting single-input electronic controller output voltages, predicting pneumatic sensor output Pressure, inaccuracies in electronic system measuring instruments and inaccuracies in pneumatic system measuring instruments[1,3].

## II. Predicting Electronic Sensor Resistance

When sensed conditions are outside the controller range, simulated conditions must be input to the controller. To do this, it is necessary to determine sensor resistance corresponding to the temperature desired. To predict the resistance of a sensor at a given temperature, the following equation is used[1]:

$$R_t = R_c \pm (X \cdot TD) \quad (1)$$

Where:

$R_t$ = Resistance (ohms) of the sensor at any temperature.

$R_c$ = Resistance (ohms) of the sensor at reference temperature.

X = Resistance constant, resistance change per unit temperature change (ohms per °F).

TD = Temperature difference from reference temperature, °F.

## III. Predicting Electronic Controller Output Voltage

In the output voltage prediction, for each system made up of a sensor-controller-controlled device, the output voltage of the controller can be predicted under various conditions. When the condition being sensed is within the throttling range of the controller, it is not necessary to disconnect the sensor from the control system to perform calibration. By predicting the output voltage for a measured parameter, such as temperature, humidity, or pressure, the performance of a particular controller may be examined[4].

The procedure is to measure the output voltage, compare the output value with the predicted value, determine the difference between the predicted and observed values, and finally calibrate the controller to make the measured value agree with the predicted value[3,5].

For example, assume a system using an integral sensor controller, with a throttling range of 4°F and a setpoint of 72°F, and calculate the output voltages for both direct and reverse acting controllers using basic pneumatic controller equation[1,6]:

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$$P_{out} = P_{sp} \pm PR \cdot ((T_1 \pm SP_1)/TR_1) \quad (2)$$

Where:

$P_{out}$ = Output or branch pressure from the controller, psig.

$P_{sp}$ = Pressure at setpoint or the pressure corresponding to setpoint temperature, 8 psig for 3 to 13 psig system or 9 psig for 3 to 15 psig system.

$SP_1$ = Setpoint temperature, °F.

$T_1$= Measured temperature of the controlled medium,°F.

$TR_1$ = Throttling range, °F, of the controller.

PR = Pressure Range of the controller as temperature changes through throttling range, 10 psig on 3 to 13 psig system or 12 psig on 3 to 15 psig system.

± = Sign for pressure change due to action; additive (+) for direct action and subtractive (–) for reverse action.

Those output voltages are found to be:

TABLE 1: OUTPUT VOLTAGE PREDICTION

| Sensed Temperature | DA Voltage | RA Voltage |
|---|---|---|
| 70°F | 6.0 vdc min | 9.0 vdc max. |
| 72°F | 7.5 vdc | 7.5 vdc |
| 74°F | 9.0 vdc max | 6.0 vdc min |

From these values it can be seen that the controller setpoint defines the center of the throttling range. A change in sensed condition of one-half of the throttling range will result in a change in output voltage (OPV) of one-half the voltage range (VR). A direct acting (DA) controller will increase OPV on increase in sensed condition. A reverse acting (RA) controller will decrease OPV on increase in sensed condition[1,2,7].

## IV. PREDICTING PNEUMATIC SENSOR OUTPUT PRESSURE

In order to predict the performance of a pneumatic receiver controller system it is necessary to start from the transmitter or sensor.

When the sensor span is known, the corresponding pressure can be predicted at any point within the sensor span.

When the sensor pressure for a particular condition is known, that pressure can be simulated as an input to the controller and the controller output pressure can be checked and adjustments made as necessary to meet the system operational requirements[1,8].

### *A. Sensor Span*

The range of linear values that may be sensed by pneumatic sensors is called the sensor span. The span may be calibrated in units for measurement of temperature, humidity, or pressure. The sensor span is the range of values over which the pressure transmitted by the sensor will vary when the sensed parameters vary from minimum to maximum[9].

Sensors are available in a variety of spans to allow selection of a span to give the best system operation. The specific spans may vary between manufacturers. As an example, pneumatic temperature sensors are available from several manufacturers with spans including –40 to 160°F, 0 to 100°F, 40 to 240°F, and 0 to 200°F. The pressure range transmitted by the sensor for each of those spans is 3 to 15 psig. Similarly, the pressure range transmitted by a relative humidity sensor having a span of 15% to 75% will be 3 to 15 psig.

### *B. Sensor Sensitivity*

The sensitivity of a sensor is defined as change in pressure transmitted by the sensor per unit of scale change. For a temperature sensor, the sensitivity is stated as the change in pressure per one degree change in temperature. The sensitivity S is a value calculated by dividing the output pressure range by the sensor span.

### *C. Prediction of Transmitted Sensor Pressure*

The pressure transmitted by a sensor at a specific temperature may be predicted by use of the following equation[1]:

$$P_S = P_L + (T - T_L) \times S \quad (3)$$

Where:

$P_S$ = Pressure transmitted at measured temperature T, psig.

T = Temperature measured, °F.

$P_L$ = Pressure transmitted at lower end of the span, psig.

$T_L$ = Temperature at the lower end of the span, °F.

S = Sensitivity of the sensor, psig/°F.

## V. PREDICTING PNEUMATIC CONTROLLER OUTPUT PRESSURE

### *A. Controller Equations*

As with electronic controls, if the condition being sensed at the sensor location is within the throttling range of the controller, it is not necessary to disconnect the sensor from the control system to perform calibration. For a pneumatic controller, to find the controller output pressure with a sensor input for a specific temperature, use equation (2).

### *B. Verification of Predicted Controller Output Pressure*

After predicting the controller branch output pressure at a sensed temperature, humidity, or pressure, it is necessary to measure and verify the controller output pressure for that specific condition. Using equation (3), a table of controller output pressures for 6°F throttling range and 10 psig pressure ranges can be constructed for various temperatures as follows:

TABLE 2: TEMPERATURE – CONTROLLER OUTPUT PRESSURE

| Temperature | Output Pressure |
|---|---|
| 78°F | 13.00 psig |
| 77°F | 11.33 psig |
| 76°F | 9.66 psig |
| 75°F | 8.00 psig |
| 74°F | 6.33 psig |
| 73°F | 4.66 psig |
| 72°F | 3.00 psig |

Note that when the sensed condition value moves outside the throttling range, the output pressure also moves outside the operating range until the limits of the main air supply are reached. For example, if the measured temperature rises to 81°F, the branch pressure of a controller with 6°F throttling range will rise to 18.00 psig or until it is equal to the main air pressure if the main line pressure is less than 18 psig.

Similarly, if the temperature drops to 70°F, the branch pressure will drop to zero. Those changes in branch output pressure will not cause any change in the system output because the actuators will have run through their full travel over the 3 to 13 psig span of the controller[1,4].

And for "Predicting Dual-input Controller Output Pressure", Equations 6 is used to predict the output of a dual input controller:

$$P_{out} = P_{sp} \pm PR \cdot ((T_1 \pm SP_1)/TR_1) \pm PR \cdot ((T_2 \pm SP_2)/TR_2). \quad (4)$$

## VI. Inaccuracies In Electronic System Measuring Instruments

When calibrating or setting up an electronic control system, the technician must recognize the inaccuracies which exist in even the most accurate components and measuring equipment. These inaccuracies may result in actual performance being slightly different than the precise values predicted by equations[2,10].

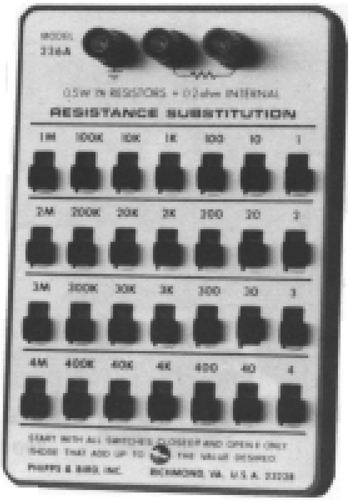


Figure 1: Decade Box (Courtesy Davis Instruments)
Sensor Inaccuracies

### A. Volt-Ohm-Milliampere (VOM) Meter

The typical accuracy for a digital VOM with a range of zero to 20.00 volts with 0.1 volt divisions, is plus or minus 0.2%. For 200 digits, the range of inaccurate readings is (± 0.2% · 200 digits) = ±0.4 digits or 0.04 volts. Thus it is seen that, when the meter is showing a voltage of 20.00 volts, the actual voltage may be as low as 19.96 volts or as high as 20.04 volts. The range of inaccuracy is 0.08 volts (20.04 - 19.96). On a controller with 6 to 9 volts output voltage and 6°F throttling range, the sensitivity is 2°F/volt. An inaccuracy of 0.08 volts times a sensitivity of 2°F/volt gives an inaccuracy of 0.016°F. This is less than the smallest scale division on the typical electronic thermometer and is therefore negligible for temperature control calibration purposes.

### B. Decade Box

The selectable resistance device, or decade box, shown in Figure 1, is often used to substitute resistance values for the analysis and simulation of conditions for set-up and calibration of electronic control systems.

A typical decade box has an accuracy to within 1%. When used with a typical VOM having an accuracy to within 0.2%, the combined accuracy of the two devices used together is calculated as:

Combined accuracy =
$[(1 – 0.01)][(1 – 0.002)] = 0.988$ or 98.8%.

A typical Balco resistance sensor has an accuracy within 0.1%. Therefore, when a VOM having accuracy to within 0.2% is used to measure the voltage output of the controller which is used along with the sensor, the combined accuracy may be calculated as follows:

Combined accuracy =
$[(1 – 0.001)][(1 – 0.002)] = 0.997 = 99.7\%$.

### C. Other Inaccuracies

Further accuracy reduction may be caused by factors such as parallax error due to the alignment of the eye to the instrument scale when reading scale values on analog gauges and meters, resolution error due to the relationship of pointer width to scale divisions and scale length, and the accuracy of other control components in the circuit. Inaccuracies may be self-canceling, where one inaccuracy may compensate for another (for example, one reading is low by the same percent as the other one is high), but the accuracy of the measurement cannot be relied upon any more than the combined accuracy of the instruments used[11].

## VII. Inaccuracies In Pneumatic System Measuring Instruments

When a pneumatic control system is to be calibrated, the technician must be familiar with the accuracy of various pieces of testing equipment so that he can take into account the inaccuracies and modify his expectation from a particular system. If the instrument inaccuracy factors are not taken into consideration and performance expectation for a system is based solely on the values predicted by equations, it is impossible to calibrate a system which corresponds exactly to the theoretical predictions.

### A. Inaccuracies in Pressure Gauges

Consider a typical pressure gauge with a dial diameter of 2.5 inches. The perimeter of this gauge is, therefore, pi times the diameter or 2.5" × 3.14 = 7.85 inches. The dial extends only through about three fourths of this perimeter or 5.89 inches. For a 0 to 30 psi range gauge, calibrated in 1 psi divisions, the length of each division is about 0.196 inches. Considering a typical gauge with a pointer having a width at the tip of 1/16" or 0.0625", the pointer width corresponds to 0.32 psi. Thus, the inaccuracy obtained in misreading a gauge by a pointer width is about 1%. A basic gauge accuracy of plus or minus 2%, plus a pointer width accuracy of 1% could give a cumulative error of 3%[11].

### B. Inaccuracies in Temperature-Calibrated Pressure Gauges

When simulating an input for a specific temperature on the controller using a temperature-calibrated pressure gauge, if the gauge has a basic 2% error and an additional 3% scale-type error is made in reading the controller input pressure, the combined accuracy of the reading may be calculated as:


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Accuracy = (1 – 0.02%)(1 – 0.03%) × 100 = 0.95%.

### C. *Other Inaccuracies in the System*

Other factors such as parallax, thickness of the indicator, and inaccuracy of other control components in the circuit may further reduce the accuracy of readings.

## VIII. Results and Discussion

In predicting electronic sensor resistance**,** equation (1) shows how the specific resistance of the sensor at any temperature may be found by adding or subtracting the changes in resistance due to temperature difference (X · TD) to or from the basic sensor resistance (Rc) at its reference temperature.

For example, to calculate the resistance for a 1,000 ohm at 70°F sensor having a resistance constant x = 2.2 ohms/°F when sensing a temperature of 180°F, the equation is:

$R180° = 1{,}000 + 2.2\,(180 - 70°F)$ ohms = 1,242 ohms .

A listing of resistance values at typical temperatures encountered in an HVAC system for a Balco sensor with a resistance of 1,000 ohms at 70°F and a constant X of 2.2 ohms/°F follows[1,2]:

TABLE 3: A listing of resistance values at typical temperatures in an HVAC system

| Temperature | Resistance |
|---|---|
| 180°F | 1,242 ohms |
| 140°F | 1,154 ohms |
| 100°F | 1,066 ohms |
| 70°F | 1,000 ohms |
| 40°F | 934 ohms |
| –10°F | 890 ohms |
| 20°F | 824 ohms |

A table of resistance values for sensors with other reference resistances and resistance constants can be obtained from the sensor manufacturers.

In Input Simulation, the required sensor resistance as calculated above is input to the controller by use of a decade box. With a constant simulated sensor input, the technician can determine whether other components are functioning in accordance with the sequence of operation.

In predicting electronic controller output voltage:

### A. *Predicting Single-input Electronic Controller Output Voltages*

Example 1:

Assume an input of 72°F, a throttling range of 4°F, a setpoint voltage of 7.5 volts, and a voltage span of 3 volts, positioning a normally closed damper actuator.

(a) First, calculate the output voltage of the controller at a temperature of 73°F. It can be seen that the output voltage is the same as under "Output Voltage Prediction" above.

Therefore, using basic electronic controller equation[1],

$$V_{out} = V_{sp} \pm VR \cdot ((T_1 \pm SP_1)/TR_1) \quad (5)$$

Where:

$V_{out}$ = Output voltage from the controller, volts dc,

$V_{sp}$ = Voltage at setpoint or the voltage corresponding to setpoint temperature, 7.5 volts on 6 to 9 volts system,

VR = Voltage Range of the controller as temperature changes through throttling range, 3 volts on 6 to 9 volts system,

$V_{out} = 7.5 \pm 3 \cdot ((73 \pm 72)/4) = 8.25$ vdc.

(b) Next, calculate the actuator positions. When the sensed temperature is 70°F, one-half the throttling range below the setpoint, the output voltage will be 6 vdc, the bottom value of the VR, and the damper actuator will be in its normally closed position. At the setpoint temperature, the output voltage will be 7.5 vdc and the actuator will be in mid-stroke, 50% open. When the sensed temperature is 74°F, the temperature at the upper end of the throttling range, the actuator will be fully open. At 6 volts, the damper is fully closed,

$6 = 7.5 \pm VR \cdot ((T_1 \pm 72)/4)$

Solving the equation results in $T_1$ = 70°F.

Example 2:

For another example, assume the control of steam supply to a humidifier using an electronic controller and

a humidity sensor with a setpoint of 30% relative humidity, a throttling range of 10% RH, and a voltage span of 10 volts, positioning a normally closed valve actuator.

(a) First, find the output voltage of the controller at a relative humidity of 28%. Using equation (5),

$V_{out} = 7.5 \pm 3 \cdot ((28 \pm 30)/10) = 6.90$ vdc.

(b) Next, find the sensed relative humidity in the space when output voltage of the controller is 6 volts. Using equation (5),

$6 = 7.5 \pm VR \cdot ((RH \pm 30)/10)$,

Solving the equation results in RH = 25%.

### B. *Predicting Dual-input Electronic Controller Output Voltage*

Assume a dual-input electronic controller used to control the temperature of hot water leaving a convertor. The controller setup parameters are:

Action = DA/DA , TR = 6°F ,Ratio = 0.51, $SP_1$ = 90°F, $SP_2$ = 58.5°F. The controller voltage span is 3 volts dc and the setpoint is calibrated for 7.5 volts dc.

Predict the output signal from the controller with an outside temperature of 50°F and a hot water temperature leaving the convertor of 100°F. In setting up a dual-input electronic controller, the throttling range for the primary variable is set directly on the controller and throttling range for the secondary variable is programmed by the ratio setting.

Ratio = ($TR_2$ / $TR_1$) or transpose to $TR_2$ = Ratio · $TR_1$,

$TR_2 = 0.51 \cdot 6°F = 3.1°F$. Then using equation (6):

$$V_{out} = V_{sp} \pm VR \cdot ((T_1 \pm SP_1)/TR_1) \pm VR \cdot ((T_2 \pm SP_2)/TR_2) \quad (6)$$

$$V_{out} = 7.5 \pm 3 \cdot ((100 \pm 90)/6) \pm 3 \cdot ((50 \pm 58.5)/3.1) = 4.27 \text{ vdc.}$$

In predicting pneumatic sensor output pressure, for example, a temperature sensor with a 40 to 240°F span and pressure range of 3 to 15 psig, the sensor sensitivity S is calculated to be:

S = (15 – 3) psig/(240 – 40°F) = 0.06 psig/°F.

using equation (5), for example, the pressure transmitted at a temperature of 190°F by a sensor with a sensitivity of 0.06 psig/°F is predicted to be:

$$P_S = 3 \text{ psig} + (190 - 40)°F \times 0.06 \text{ psig}/°F = 12 \text{ psig}.$$

It is important to note that the pressure equivalent to a specific temperature on a sensor of a given span will be different from the pressure equivalent to the same temperature on a sensor of a different span.

Consider the case of two sensors measuring the same temperature, where sensor A has a span of 0 to 100°F, sensor B has a span of 40 to 140°F, and both sensors have a pressure range of 3 to 15 psig. At a temperature of 50°F, the pressure transmitted by sensor A will be 9 psig and the pressure transmitted by sensor B will be 4.2 psig.

In predicting pneumatic controller output pressure, as an example, assume a direct-acting, single-input controller with a 50 to 100°F temperature sensor, 6°F throttling range, 75°F setpoint, and branch pressure range of 3 to 13 psig or 10 psig. The midpoint output pressure for the 10 psig range system corresponding to the setpoint value is equal to the 3 psig lower value plus one-half of the 10 psig pressure range, or 3 psig plus (10/2) psig = 8 psig.

For systems with a 3 to 15 psig range, the midpoint pressure is 3 psig plus (12/2) psig = 9 psig. To determine the branch output pressure of this controller at a temperature of 77°F, use equation (2) as follows:

For 10 psig pressure span,

$$P_{out} = 8 \pm 10 \cdot ((77 \pm 75)/6) = 11.33 \text{ psig}.$$

For 12 psig pressure span,

$$P_{out} = 9 \pm 12 \cdot ((77 \pm 75)/6) = 13 \text{ psig}.$$

Finally, about inaccuracies in electronic and pneumatic systems measuring instruments, recognized that when calibrating or setting up electronic and pneumatic control systems, the technician must recognize the inaccuracies which exist in even the most accurate components and measuring equipment. These inaccuracies may result in actual performance being slightly different than the precise values predicted by equations.

## IX. Conclusions

Performance prediction is the process of calculating what the output of the controller should be, based on the conditions being sensed and controlled. Performance prediction is one step in the overall calibration procedure. In this paper, we surveyed performance prediction algorithms for control systems in HVAC systems that contain predicting resistance, predicting output voltage, predicting output Pressure, inaccuracies in pneumatic and electronic measuring instruments. When sensed conditions are outside the controller range, simulated conditions must be input to the controller. To do this, it is necessary to determine sensor resistance corresponding to the temperature desired. The procedure is to measure the output voltage, compare the output value with the predicted value, determine the difference between the predicted and observed values, and finally calibrate the controller to make the measured value agree with the predicted value. in electronic and pneumatic systems measuring instruments, recognized that when calibrating or setting up electronic and pneumatic control systems, the technician must recognize the inaccuracies. These inaccuracies may result in actual performance being slightly different than the theoretical predicted values.

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