A REVIEW OF STATISTICAL MEASUREMENT ASSURANCE TECHNIQUES APPLIED TO FLOWMETER CALIBRATION

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Abstract: In March 1999 the CEESIowa facility went into operation for the calibration of large line size ultrasonic meters used for natural gas custody transfer. This paper describes three statistical measurement assurance techniques applied to the calibration of large ultrasonic flowmeters for natural gas applications. First, several flowmeter check standards have been in use for four years to maintain control charts that confirm consistent performance of the calibration process. Second, an intercomparison test program allows for the turbine standards to be compared to each other. The final technique allows for the separation of random effects from different sources through the use of multiple test articles.

1. INTRODUCTION

The CEESIowa calibration facility has been operational since March 1999 [1]. It is located adjacent to a custody transfer station on a pipeline operated by the Northern Border Pipeline Company. Control valves bypass gas through a parallel array of nine 305 mm (12") turbine meters that serve as flow standards. One or more turbine meters are opened to achieve a particular flowrate. The gas exits the turbine meter array and flows through one of three test sections. Three test sections allow for the calibration of a range of meter sizes and installation conditions. With normal pipeline operation the test section pressure is between 6.9 and 7.6 MPa (1000 and 1100 psia). Nominal test section diameters are 508 mm (20”), 610 mm (24”), and 762 mm (30”).

2. STATISTICAL PROCESS CONTROL

Two ultrasonic flowmeters, 508 mm (20”) and 610 mm (24”) in size, have been permanently installed in two of the three test sections. More recently 305 mm (12”) turbine and ultrasonic meters have been installed in the third test section. Data are obtained from one of these meters during every calibration performed on a client meter. The purpose of these meters is to serve as check standards that confirm consistent performance of the calibration facility. In other words, the consistency of a particular set of check standard calibration data is strong evidence for the validity of the corresponding client meter calibration data. The statistical technique applied to quantify the consistency of the check standard meter data is called statistical process control (SPC) [2].

2.1. Methodology

The SPC tool used in the Iowa facility is control charting; the development of that tool is described in this section. As a typical example, the results from the 610 mm (24”) ultrasonic meter will be presented. Each data point obtained on a meter under test (MUT), includes a simultaneous data point obtained on the check standard. A typical MUT calibration includes 30-40 data points, the simultaneous check meter data are accumulated over time. The 610 mm meter was included in calibrations performed on 180 days (7743 data points) between August 2000 and June 2004.

The meter performance is defined by a K Factor and confidence interval. The K Factor is the difference between meter indications and calibration values for volumetric flowrate. A curve fit relates K Factor and velocity. The 95% confidence interval about the curve fit is the statistical interval that contains 95% of the data. The interval width is $\pm 2s_{ci}$ where:

$$s_{ci} = \left(av^{b} + c\right)\% \qquad (1)$$

and v is velocity [m/s]. Typical data for this meter are shown in Figure 1. The shape of the curve clearly shows two effects that are typical for flowmeter calibration data. The “percent of full scale” effects are represented by av^b while “percent of reading effects” are represented by c.

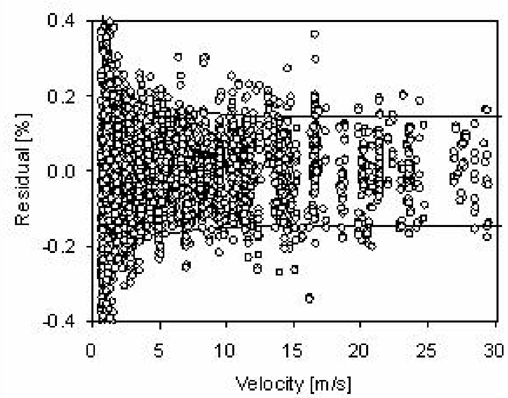

Fig. 1 Typical Ultrasonic Meter Data

A pair of control charts is constructed based on the historical data obtained from the check standard. The two charts, shown in Figures 2 and 3, represent the variation in daily mean and standard deviations normalized based on Eq. 1. The normalization allows for comparing high and low velocity data without bias. The normalized results are expressed in units of standard deviation.

The open circles in Figs. 2 and 3 represent daily data, the lines represent control limits. The control limits monitor the consistency of the process. If the process remains consistent, most of the data points in Fig. 2 remain between the limits. A few data points (up to 5%) can lie outside the limits associated with a consistent process because the limits are defined at a 95% level of confidence. Inconsistent performance is indicated when more than 5% of the data points lie outside the limits. The discussion above is applicable to the control chart of Figure 3 except that 95% of the data points must lie below the single control limit. The details of calculating control limits are described in Reference 1.

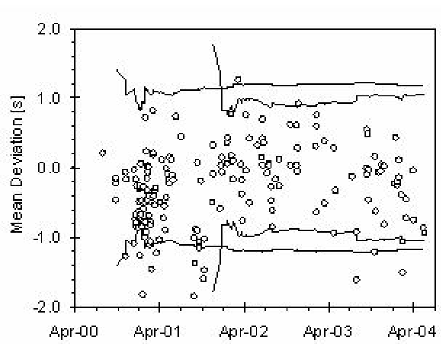

Fig 2. 610 mm Check Standard Control Chart

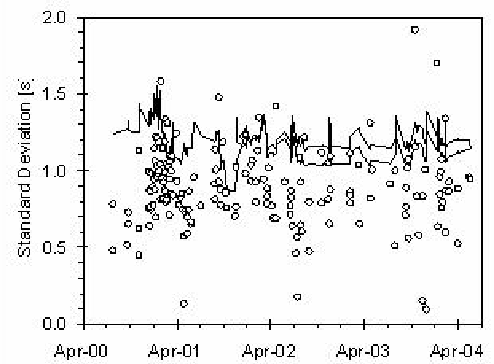

Fig 3. 610 mm Check Standard Control Chart

The charts show new control limits that begin in January 2002, these limits are calculated based on a new curve fit. Improved performance is noted in Fig. 2, the lines form a narrower interval. The control chart of Fig. 3 does not indicate improved performance; both lines are nearly coincident. The control chart is a powerful tool in evaluating the effect of changing a process, in this case applying a new curve fit.

The control charts for this meter exhibit very consistent performance for the most recent 24 months (December 2001 to December 2003). The performance prior to December 2001 exhibits slightly lower mean values, a shift in the performance of either the meter or the facility. Comparing results from all four check meters will help to localize the performance shift.

2.1. Uncertainty Considerations

The calculations used to create control chart limits are applicable to estimating the uncertainty of the process. The control charts require two values of standard deviation, s_w and s_b, which account for short and long term random effects. The reported standard deviation, s_r, accounts for both categories of random effects:

$$s_r = \sqrt{s_b^2 + s_w^2} \qquad [2]$$

In the present application the reported standard deviation accounts for all the random effects associated with the facility operation. These effects are contributed by the pressure and temperature instruments and gas chromatograph as well as the turbine meter standards. Also included are the random effects associated with the check standard itself. The traditional approach to uncertainty analysis is to account for the random effects contributed by the various components. The control chart analysis provides independent support to the traditional approach based on a range of historic data to estimate this component of uncertainty [3].

2.2. Other Check Meters

Three additional meters are used as check standards in the facility [1]. Two ultrasonic meters, 508 mm (20”) and 305 mm (12”) in size, and a 305 mm turbine meter. The 508 mm meter failed in service and a replacement preamplifier board did not result in performance consistent with the earlier history. The electronics and transducers for this meter are being replaced. The 305 mm turbine meter continues to indicate consistent performance. The SPC methodology has not yet been applied to the 305 mm ultrasonic meter history.

3. TURBINE SUBSTITUTION TESTING

A typical control chart involves several flow standards, particularly at the higher flowrates. A slight shift in the performance of one standard can therefore go undetected; the effect of the shift is reduced in proportion to the number of flow standards in use. The turbine substitution test (TST) has been developed to confirm the absence of any turbines meter shifts based on intercomparison testing [3]. The TST data provide a strong complement to the SPC data.

A turbine substitution test is implemented as follows. One of the turbine standards is connected in series with a test artifact, stable flow is established and data points are recorded. Control valves divert the flow through a different turbine standard without changing the flowrate. After the flow transients have dissipated a second set of data points are obtained. A third turbine meter is substituted for the second and additional data are obtained. This process continues with different standards until all turbines have been tested.

Two types of test artifact have been used. The first is the meter under test (MUT) present in nearly all TST. A calibration will have just been completed; these data are used to determine the MUT performance at the flowrate of interest. The second artifact type is the SPC check standard, the performance at the flowrate of interest is determined from the historical data. Most of the TST artifacts are turbine or ultrasonic type meters; several TSTs were performed using orifice meters as artifacts. In many cases two artifacts are installed, in some cases there are three or four.

The TST database currently contains 7493 data points from 64 tests performed on a regular basis since July 1999. The results of a TST consist of a series of data points, K Factor and flowrate, that are collected for each turbine standard. The accumulated results for each turbine standard have been used to determine the best possible relationship (curve fit) between K Factor and flowrate.

Typical recent data are contained in Figure 4. The ordinate shows curve fit residuals, the abscissa shows flowrate. The plot contains results for seven turbine meters obtained between March 2003 and February 2004. The standard deviation of all the data points (1232) is 0.091%; the standard deviation is reduced to 0.085% if 29 of the data points are excluded. These values represent the uncertainty contributed by all the random effects present during a typical TST.

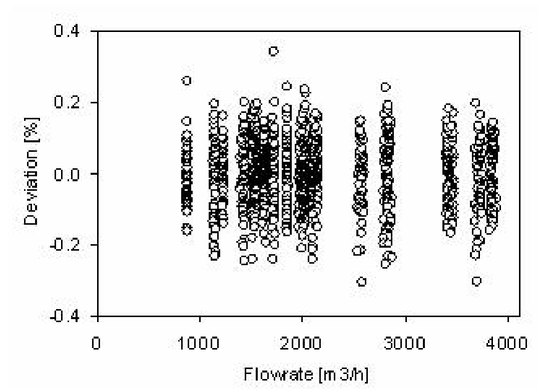

Fig 4. Turbine Substitution Test Data

A similar analysis was completed in October 2001 [3]. The results are similar except that the older analysis indicated a standard deviation that varied with flowrate. The present analysis shows no such variation. The difference is attributed to the smaller size of MUT and check standard present in the current testing. A smaller meter allows for TST data to be obtained at a flowrate high enough in the meter range to minimize full-scale effects.

4. YOUDEN ANALYSIS

Traditional analysis of SPC and TST data cannot separate random test effects from effects of shifting flowmeters. A different technique, called “Youden analysis" is applied [4] to separate these effects. The methodology is described based on presentation of data in the two sections below.

4.1. SPC Data Analysis

The 305 mm turbine and ultrasonic flowmeter check standards have been operating in series since April 2003. The simultaneous data from these two meters provides an opportunity for a Youden analysis. While there is some correlation associated with any two flowmeters in series, a large degree of independence is achieved because flowrate is measured using two different technologies.

The Youden analysis is based on the graph contained in Figure 5. Each symbol represents a data point; the ordinate and abscissa represent the residuals from the turbine and ultrasonic check standards. The results have been normalized by forms of Eq. 1; the plotted values are expressed in units of standard deviation.

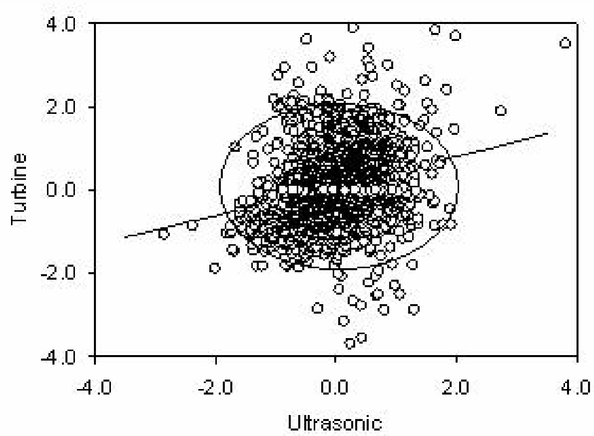

Fig 5. Typical SPC Youden Plot

The graph of Fig. 5 contains 1584 data points obtained between April 10 and August 18, 2003. Individual data points can deviate from the center of the plot in any direction due to random effects present in either of the two check standards. The circle on the plot has a radius equal to two standard deviations; it would be expected to contain 95% of the data points. The straight line is a regression of those data points that lie near or within the circle.

Approximately 45 data points lie well above and below the circle; the turbine meter is indicating a higher or lower flowrate than the ultrasonic meter. The remaining data points fit within the circle. The analysis has indicated that a systematic (non-random) effect is present with a few turbine meter data points. This effect is not likely present in the calibration facility because it is not observed. Additional analysis of the data should isolate the source of this systematic effect.

The second structure on the plot is a regression line fit to the remaining 1529 data points, those discussed above having been excluded. The line has a positive slope that indicates the potential presence of effects common to both check standards. A positive slope, particularly a unity slope, represents conditions where both check standards read high or low. While a regression line can be calculated, the correlation is weak. In Fig. 5 approximately 8% of the variation in the turbine meter is correlated with variation in the ultrasonic meter. A unity slope and higher degree of correlation would indicate the presence of an effect common to both check standards, potentially an effect associated with the calibration facility itself.

In the present application it is concluded that the Youden analysis does not indicate a variation associated with the facility. It does indicate some unusual behavior with the 305 mm turbine meter check standard. The analyses described in Reference 4 illustrate Youden plots where highly correlated systematic effects are present.

4.2. TST Data Analysis

The Youden analysis technique is applied to TST data when data from more than one artifact are available. Typical data, for a single turbine meter (identified as TM 241), from a single TST (identified as TST 60), are contained in Figure 6. The open symbols represent data from the 305 mm turbine and ultrasonic check standards. The solid symbols represent data from two customer meters, both 305 mm (nominal) in size. The test consisted of 280 data points from the four artifacts, 96 of which were obtained using TM 241. The data were normalized, the standard deviations varied between 0.057% and 0.086% for the four artifacts. The values are expressed in units of standard deviation. The circle on the plot has a radius equal to two standard deviations.

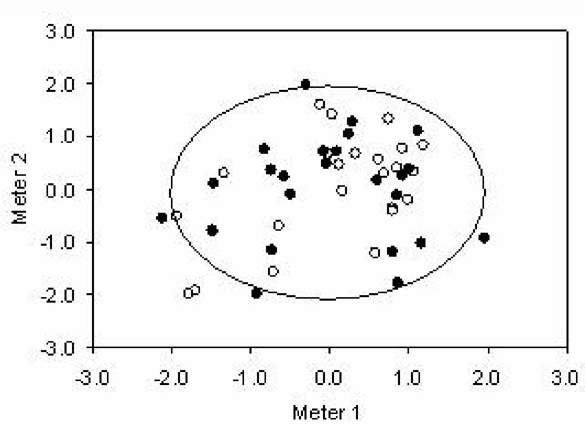

Fig 6 Typical TST Youden Plot

Most of the data in Fig. 6 are uniformly distributed near or within the circle. This indicates that the test process results are dominated by random effects, no common (systematic) effects are observed. If systematic effects were observed in the present application they would likely be due to TM 241. Regressions were fit to both data sets, the results are not shown in Fig. 6. There is no correlation between the two customer meters while 30% of the variation in one check standard is correlated with variations in the other. Additional analysis of the data should isolate the source of this apparent systematic effect.

5. CONCLUSIONS AND RECOMMENDATIONS

A brief description of three statistical measurement assurance tools has been presented. These tools are applied to the operation a flowmeter calibration facility. The primary tool, statistical process control (SPC), monitors the results from check meters to quantify the overall process consistency. The second tool confirms the absence of any differences between the multiple flow standards. The third tool, helps identify the source of observed random effects. Taken together, the three tools assure that the uncertainty of the calibration results meet the customer requirements.

It is recommended that similar tools be included as an important part of the measurement assurance program for any calibration process. The range of statistical techniques is currently being expanded for the facility described in this paper.

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