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Pressure balance cross-calibration method using a pressure transducer as transfer standard

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Abstract

Piston gauges or pressure balances are widely used to realize the SI unit of pressure, the pascal, and to calibrate pressure sensing devices. However, their calibration is time consuming and requires a lot of technical expertise. In this paper, we propose an alternate method of performing a piston gauge cross calibration that incorporates a pressure transducer as an immediate *in-situ* transfer standard. For a sufficiently linear transducer, the requirement to exactly balance the weights on the two pressure gauges under consideration is greatly relaxed. Our results indicate that this method can be employed without a significant increase in measurement uncertainty. Indeed, in the test case explored here, our results agreed with the traditional method within standard uncertainty, which was less than 6 parts per million.

1. Introduction

Piston gauges or pressure balances are important devices for the realization and dissemination of the SI unit of pressure, the pascal (Pa). They make use of the simple relationship of pressure to the units force and length, pressure being an intrinsic property that is equal to the amount of force applied to a unit area. They are accurate on the order of several parts per million, and useful over a broad pressure range spanning several orders of magnitude from tens of kilopascal (pressures below an atmosphere) to several hundred megapascal. NIST has two pneumatic primary standard piston gauges that were characterized by careful dimensional measurements and modeling of fluid forces on the piston, and compared for agreement within stated uncertainties against an ultrasonic interferometer manometer. These were used to calibrate working standard piston gauges that are in turn used for calibrations of test or customer gauges using the cross-float method spanning the range from 10 kPa to 280 MPa. The cross-float method has been in use at NIST for more than forty years. It involves using the NIST gauge to generate a known pressure, and adjusting the forces on the test gauge (by adding or removing masses) to achieve a balance condition. With the forces balanced and knowing the pressure generated by the NIST gauge, the effective area of the test gauge can then be calculated. The effective area is the quantity of interest in a piston gauge; it is the quantity that when combined with the loaded forces on the gauge produces the pressure. Conceptually this is a simple process, but

it requires many hours of attention from an experienced metrologist who must assess the state of the gauges during a cross-float (either using a differential pressure cell or by measuring the fall rate of the piston in the cylinder) and add or remove tiny trim masses by hand to achieve the balance condition. We propose a modification to the cross-float calibration method wherein a pressure transducer is used as a very short-term transfer standard between the two piston gauges. It will allow for a much less stringent balance condition and lends itself to automation. If combined with a robotic means of loading masses onto the gauge, automated pressure generation, and piston float, this will enable full automation of piston gauge calibrations. In this experiment, we compare such a calibration with a traditional cross-float. Our findings indicate that we will be able to achieve uncertainties comparable to those from the traditional cross-float method, in this case less than 6 parts per million (ppm).

2. Method

The transducer-aided calibration (TAC) [Roman font] differs from the usual cross-float in that a near-perfect balance condition is no longer required for an accurate calibration. The set-up is similar; NIST and test piston gauges are placed on a workbench, leveled, and plumbed into a manifold with gas supply (in this case, nitrogen), volume changer or pressure controller for fine gas pressure adjustment, and shut-off valves to isolate the various components as necessary. In the place of the differential pressure cell, a 3.175 mm three-way stainless steel ball valve connects either of the two piston gauges to a transducer (Paroscientific, model 6000-200 G)¹.

Based on the effective area of the reference gauge (known from precise dimensional analysis) well characterized known masses are added to the reference gauge to generate a desired pressure. Masses are added to the test gauge to nominally the same pressure. In a traditional cross-float, a metrologist then adds or removes trim masses until balance was achieved between the two piston gauges to within the resolution of the differential pressure cell—typically less than 1 in 10^6 . In the TAC method this is unnecessary. Instead, the pressure of the NIST gauge is sampled by the transducer. The transducer is then closed to the NIST gauge and opened to the test gauge. If the transducer reading is sufficiently reproducible and linear, it can be employed as an immediate, short-lived, in-situ transfer standard; The NIST gauge calibrates the transducer and that calibration is immediately transferred to the test gauge. If the transducer reading is a linear function of the actual pressure, it can be expressed in the usual way, $P_{trans} = lP_{actual} + b$, [omit X for times here and throughout] where the slope l and zero-offset b are properties of the transducer that are ideally but not necessarily independent of pressure. In equation (1), the offset between the transducer reading and the NIST gauge is adjusted for linearity and added to the reading of the test gauge to find the actual pressure on the test gauge,

Disclaimer: Certain equipment or materials are identified in this paper in order to specify the experimental procedure adequately. Such identification is not intended to imply endorsement by the National Institute of Standards and Technology, nor is it intended to imply that the materials or equipment identified are necessarily the best available.

$$P_{\text{actual,test}} = \frac{P_{\text{trans,test}} - P_{\text{trans,std}}}{l} + P_{\text{actual,std}} = \frac{\Delta P}{l} + P_{\text{actual,std}} \quad (1)$$

The slope l needs to be characterized in a separate measurement, but the zero-offset of the transducer is negligible, so long as it doesn't change appreciably on a timescale on the order of seconds. The force on either gauge is given by equation (2),

$$F = P A_{\text{eff}} = \frac{\sum_i m_i g (1 - \rho_a / \rho_b) + \gamma C}{1 + (\alpha_p + \alpha_c)(T - T_r)}, \quad (2)$$

Where ρ_a is the air density, ρ_b is the density of the pressurizing medium, T_r is the reference temperature (typically 23 °C) α_c and α_p are the thermal expansion coefficients of the cylinder and piston, respectively. Note that the surface tension term, γC , is zero for gas

pressurizing media, the term $(1 - \rho_a / \rho_b)$ is to correct for buoyancy, and the denominator is correction for deviation of the actual temperature from the reference temperature. The measurement equation pressure P_T of the test gauge using the *TAC* method thus becomes:

$$P_T = \frac{\Delta P}{l} + \left(\frac{1}{A_{\text{eff}}} \right) \frac{\sum_i m_i g (1 - \rho_a / \rho_b)}{1 + (\alpha_p + \alpha_c)(T - T_r)}. \quad (3)$$

The effective area of a general piston gauge is related to the force by eq(4) [2],

$$A_{\text{eff}} = A_0 (1 + b_1 P + b_2 P^2) - t/P \quad (4)$$

where the coefficients A_0 , b_1 , b_2 , and t are determined by calibration. Equations (2) and (4) are combined to calculate the actual pressure generated by the NIST gauge, and the actual pressure on the test gauge is calculated using equation (1).

3. Characterization of transducer

We characterized the stability, repeatability, and linearity of the transducer as follows. To assess repeatability, masses were added to both gauges and the three-way valve was switched several times to connect either gauge to the transducer in turn. Transducer readings were recorded at about 1 Hz. The transducer was sampled approximately ten times on one gauge before switching to the other gauge. A point is considered an average of these readings during a single sampling of the transducer at either gauge. At a given pressure, between two and six points were taken for each gauge. The initial set of points were taken with the gauges balanced to within 5 Pa. Masses were added to the test gauge and this process was repeated a total of six times, covering a pressure range from 355.95 kPa to 357.40 kPa. The largest pressure difference between the standard and test gauge was $P =$

1.5 kPa or 0.4%, which is significantly larger than would be acceptable in a traditional cross-float (about 0.4Pa). In all cases, at a given pressure each time the transducer was switched between gauges the point returned to the same value within statistical uncertainty, that is, the effect of switching has undetectable influence in the overall result because it is below the noise. A similar repeatability test was performed at a nominal pressure of 80 kPa, in which the pressure difference was allowed to be as large as $P = 2.7$ kPa. Again we observed the pressure returning to the same value after switching between the standard and test gauges.

See Figure 2, error bars are one standard deviation. In addition, we verified the stability of the transducer at a representative pressure. After waiting ten minutes for stability, data were collected over approximately 30 minutes at a single pressure near 356 kPa (generated by reference gauge, in this case NIST standard PG34) and the overall drift was found to be less than 2 mPa/s, well below the resolution of the gauge. (Figure 3).

Given that readings are taken at about 1 Hz, and that a calibration at a single pressure will take on the order of seconds or at most minutes, if drift is at or below 1 Pa/MPa level at a single pressure, it can be ignored. From this we can conclude that the transducer readings are sufficiently repeatable, even for pressure differences as high as 1 kPa (possibly much higher – other factors limited P for these tests as will be explained below). We found no evidence of hysteresis associated with increasing versus decreasing pressure on this mass and time scale. We characterized the linearity of the transducer by generating a known pressure on the standard, and increasing it in small increments. The transducer readings are graphed vs pressure in Figure 5. A linear fit was performed to find the best value for the slope I with

associated uncertainty σ_I found by linear regression analysis, $\sigma_I = \sigma_t \sqrt{1 / \sum (P_i - \bar{P})^2}$ where P is the actual pressure generated by the standard, $\bar{P}$ is the average pressure, and σ_t is

the standard uncertainty $\sigma_t = \sqrt{\sum (P_{t,i} - \hat{P}_{t,i})^2 / n - 2}$ of the mean of the n transducer readings P_t , where $\hat{P}_t$ is the value of P_t predicted by the linear fit. We find that we can establish the slope of this transducer to less than 10^{-6} . For example, at around 365 kPa, $I = 0.9998919$ and $\sigma_I = 6 \times 10^{-7}$. The value of the slope I is potentially important in the calibration as it shows up in the denominator of equation (1) and contributes to the overall uncertainty at the 10^{-6} level, it needs to be established to an accuracy of 10^{-6} or better (see following section). This is within the specifications of a high-quality commercially available transducer, roughly corresponding to a resolution of 0.0001%.

It is worth pointing out that I may not be entirely determined by the transducer, but may be conflated with distortion or other effects of the piston gauges themselves. Further work is planned to investigate this question, but for purposes of this discussion, this slope need only be characterized for the system at hand in order to be used as a calibration factor, regardless of its provenance.

4. Experiment Details

We tested this method using two well-characterized NIST piston gauges, one was used as a standard (NIST ID: PG34) and one was used as a test gauge (NIST ID: C415). The gauges

were set up and plumbed in with the transducer via a three-way air-actuated solenoid valve. A differential pressure cell was plumbed into the same manifold to allow real-time cross checking of the *TAC* method against the traditional method. The system was leak tested, and allowed to thermally equilibrate overnight. At each of eleven pressures, first a point was taken with the DP cell (traditional method) and then a series of about ten points within about 3% of that pressure were taken using the transducer (*TAC* method). We compared the results from these two methods, as well as comparing this traditional cross-float to the historical results from calibration against the appropriate NIST primary standard.

4.1 Traditional Cross-Float

Consider first the traditional cross-float. The test gauge was floated against the standard gauge at eleven different pressure points. The temperature-corrected forces were calculated in the usual way using equation (2). The effective area of the gauge could then be calculated from the pressure generated by the standard gauge—using known masses and pre-determined calibration coefficients for the gauge in equation (4)—at each pressure point, see Figure 5. The data are fit to a linear function and extrapolated to zero to get a final value for the effective area of $A_{\text{eff}} = 8.400674 \times 10^{-5} \text{m}^2$.

The type A standard uncertainty associated with this result is

$$u_{\text{typeA}} = \left(u_{A_0}^2 - (A_0 u_{b1} \bar{P})^2 + (A_0 u_{b1} (P - \bar{P}))^2 \right)^{1/2} \quad (5)$$

where

$$u_{A_0} = \sigma_A \times \sqrt{\frac{1}{n} + \frac{\bar{P}^2}{\sum (P_i - \bar{P})^2}} = 3.9 \times 10^{-11} \text{m}^2 = 0.47 \text{mm}^2/\text{m}^2. \quad (6)$$

And

$$u_{b1} = \frac{\sigma_A}{A_0} \times \sqrt{\frac{1}{\sum (P_i - \bar{P})^2}} = 5.26 \times 10^{-10} \text{Pa}^{-1} \quad (7)$$

where σ_A is the standard uncertainty of the mean,

$\sigma_A = \sqrt{\sum (A_i - \hat{A}_i)^2 / n - 2} = 6.4 \times 10^{-11} \text{m}^2$ A_i is the i^{th} point, and $\hat{A}_i$ is the value of that point predicted by the linear fit. equation (5) is a function of pressure and evaluates to between 0.46 and 0.59 mm^2/m^2 .

In the traditional cross-float, the type B uncertainty is dominated by two components, the uncertainty of the effective area ($u_{A_{\text{eff}}}$) of the standard and that of the masses on both gauges (u_M). The type B uncertainties associated with the standard (in this case PG34) piston gauge effective area are calculated using equation (4) below [2]:

$$u_{A_{\text{eff}}}/A = \left[\left(\frac{c_1}{p} \right)^2 + c_2^2 + (c_3(p - p_{av}))^2 + (c_4 p)^2 \right]^{1/2} \quad (8)$$

where the coefficients c_1 , c_2 , c_3 , c_4 , and p_{av} are pre-determined by the calibration of the standard. For this measurement, equation (5) evaluates to between 4.2 ppm and 4.9 ppm over the pressure range considered (80 kPa to 1450 kPa). The uncertainty due to the masses on the standard gauge u_{MS} is

$$u_{MS}/A = - \frac{1}{\sum_i m_{i,s}} \sum_i u(m_{i,s}). \quad (9)$$

The masses on the standard gauge are correlated together, but they are uncorrelated to the test masses. Following ref [2], because the individual masses have a relative uncertainty of 2 mg/kg, the relative uncertainty on the effective area is 2 mPa/kPa. Likewise the test masses contribute 2 mPa/kPa uncertainty. Additionally, we consider temperature and thermal expansion (α) uncertainties. These relative uncertainties evaluate to $u_{temp} = 0.5 \times 10^{-6}$ and $u_\alpha = 0.5 \times 10^{-6}$ for each gauge.

Thus the overall type B uncertainty associated with this measurement is

$$u_B/A = \left[\left(\frac{u_{A_{\text{eff}}}}{A} \right)^2 + \left(\frac{u_{M,s}}{A} \right)^2 + \left(\frac{u_{M,t}}{A} \right)^2 + \left(\frac{u_{temp,s}}{A} \right)^2 + \left(\frac{u_{temp,t}}{A} \right)^2 + \left(\frac{u_{\alpha,s}}{A} \right)^2 + \left(\frac{u_{\alpha,t}}{A} \right)^2 \right]^{1/2} \lesssim 5.8 \text{ mm}^2/\text{m}^2. \quad (10)$$

Added in quadrature to the type A uncertainty, this results in standard combined uncertainty values ranging from 5.1 ppm to 5.8 mm²/m².

4.2 Transducer-Aided Cross-float

The test gauge was calibrated at eleven pressures spanning the range of the gauge (80 to 1450 kPa). At each of these pressures, approximately ten points were taken with varying pressure differentials between the standard and test gauges (P). Typical data are plotted in Figure 6 at a pressure around 494 kPa, with the effective area as calculated by equation (1) with slope I assumed to be 1.

Equations (2) and (4) are used to calculate the pressure generated by the standard as usual, and equation (1) in combination with the transducer readings is used to calculate the pressure and effective area of the test gauge (using force values calculated for the test gauge from equation (2)). The effective area was calculated with the correct slope I and compared to a similar calculation in which the slope was assumed to be unity. The latter represents a much more convenient real-life approach, because the act of determining the slope requires

tedious loading of trim masses. Both of these *TAC* method results were compared to results obtained by a traditional cross-float, discussed in the results section below. The type B uncertainties in a traditional cross-float are dominated by the uncertainties in the effective area of the standard and masses as described above, and this is still true for the *TAC* method, but the uncertainty introduced by the transducer must be considered as well. There are three quantities in the measurement equation (equation 3) that need to be considered; $P_{\text{trans, test}}$, $P_{\text{trans, std}}$, and l .

The uncertainty in P_T due to $P_{\text{Trans, test}}$ is calculated by taking the partial derivative of equation (3)

$$u_{P_{\text{Trans, test}}} = \frac{\partial P_T}{\partial P_{\text{Trans, test}}} u(P_{\text{Trans, test}}) = \frac{1}{l} \times u(P_{\text{Trans, test}}) \approx u(P_{\text{Trans, test}}) \quad (11)$$

which is just the statistical uncertainty in the transducer. Similarly $u_{P_{\text{Trans, std}}} = u(P_{\text{Trans, std}})$. The uncertainty in P_T due to l is calculated by taking the partial derivative of equation (3)

$$u_l = \frac{\partial P_T}{\partial l} u(l) = -(\Delta P / l^2) u(l) \quad (12)$$

where $P = P_{\text{trans, test}} - P_{\text{trans, std}}$ and $u(l)$ is the uncertainty in the slope as described above.

As P gets larger, it becomes more difficult to keep both gauges floating and spinning while switching back and forth between them with the transducer. The allowable size of P depends on system particulars and will need to be determined by the experimenter at the time of calibration, but it is worth remembering that the ultimate goal is to eliminate the need for trim masses. If the regular (not trim) masses in a set differ by m , then so long as the $P_{\text{max}} > m g / A_{\text{eff}}$, this goal has been achieved. The manifold should be constructed in such a way as to minimize changes in volume when gauges are operated because such changes are liable to disrupt the balance condition. In this case, the gauges could be operated well enough when P grows as large as about 3%.

For the transducer we're using, it's reasonable to assume we can establish $u(l)$ at any pressure to less than about one part per million. Furthermore, for any reference grade transducer l will be close (certainly within a percent) to unity. So,

$$u_l = \frac{\Delta P}{l^2} \times u(l) \approx \Delta P \times 10^{-6} \quad (13)$$

And thus even if P can be as large as 10%, the uncertainty on the effective area of the test gauge due to the slope of the transducer is

$$u_l \lesssim 1 \times 10^{-7} \quad (14)$$

and is therefore negligible.

For example, in this calibration, take $P = 2.7$ kPa at the 80 kPa point. The slope in the region of interest is $l = 0.999892$ and the uncertainty in the slope is 2.6×10^{-8} , so the contribution to the overall uncertainty is

$$u_l = \frac{\Delta P}{l^2} \times u(l) = 3.2 \times 10^{-8} \text{ kPa (negligible)}. \quad (15)$$

The total uncertainty is similar to eq(10), but with additional terms $u_{P,\text{trans,test}}^2 / A$ and $u_{P,\text{trans,std}}^2 / A$.

5. Results

The results for the effective area at zero pressure of NIST gauge C415 from the two methods under comparison are

$$A_{\text{eff},0 \text{ crossfloat}} = 8.400674 \times 10^{-5} \text{ m}^2 \pm 4.59 \times 10^{-10} \text{ m}^2.$$

for the traditional cross float and

$$A_{\text{eff},0 \text{ TAC, real slope}} = 8.400675 \times 10^{-5} \text{ m}^2 \pm 4.63 \times 10^{-10} \text{ m}^2 \text{ and}$$

$$A_{\text{eff},0 \text{ TAC, ideal slope}} = 8.400668 \times 10^{-5} \text{ m}^2 \pm 4.58 \times 10^{-10} \text{ m}^2$$

for the transducer-aided calibration, uncertainties reported at the $k = 1$ level. These can also be compared to a previous cross-float calibration of this piston gauge in which the effective area was found to be

$$A_{\text{eff, historic}} = 8.400696 \times 10^{-5} \text{ m}^2 \pm 3.6 \times 10^{-10} \text{ m}^2.$$

The traditional cross-float agrees with this historical value to less than $3 \text{ mm}^2/\text{m}^2$. As shown in Figure 7, the results from the three different methods are in very good agreement. In fact, the *TAC* method differs from the same-day cross-float method by less than $1 \text{ mm}^2/\text{m}^2$, regardless of whether or not one uses the real slope l or the ideal slope $l = 1$.

So we can conclude that calibrations by the *TAC* method can be made that are in sufficient agreement with cross-float calibrations, so long as a transducer is chosen which has sufficient resolution, linearity, and stability characteristics in the pressure range of interest. Adoption of the *TAC* method will reduce metrologist time and necessary expertise without introducing any significant error or uncertainty, and is an important step in total calibration automation. The authors caution that because transducer behavior has been observed in some cases to change over time, the behavior of the transducer should be monitored for long-term consistency.

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Figure 1. schematic diagram of experimental setup for (a) the traditional cross-float method and (b) the TAC method (retaining DP cell for diagnostic reasons).

Figure 2.
Repeatability at 356 kPa and 80 kPa.

Figure 3.
Drift in transducer reading at constant real pressure (356.000 kPa).

Figure 4.

Linearity around 80 kPa. From these data the slope is found to be $I = 0.99980902234$ and the uncertainty in the slope is $u_1 = 3.2 \times 10^{-10}$. Similar measurements were carried out over the entire range of the test and in all cases $I \approx 1$.

Figure 5.
Effective area determined by traditional cross-float. Error bars are ± 1 standard deviation.

Figure 6.
Comparison of TAC method to traditional method using DPI at a single pressure (494 kPa).

Figure 7. Effective area from the traditional method (squares), the TAC method with linear fit (solid diamonds) and the TAC method with $l = 1$ (open diamonds). Error bars include statistical and systematic uncertainty and are reported at the $k = 1$ level.