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Calibration

PG7000 high line differential mode for defining differential pressure at line pressures above atmospheric pressure (PG7000 V2.03 and higher)

Technical Note

Pressure measuring devices intended to measure differential pressure at line pressure well above atmospheric pressure are widely used. These are often calibrated in gauge mode, leaving the low side open to atmosphere and applying known pressures relative to atmosphere to the high side. However, the very high ratios of the line pressure to atmospheric pressure and to the differential pressure are likely to cause significant differences in the device's response to differential pressure when operating at atmosphere and at the normal elevated line pressure. Applying a common pressure simultaneously to both sides of the device easily quantifies changes in zero with line pressure. To determine the influence of line pressure on differential pressure span, a pressure standard able to define differential pressures at elevated line pressures must be available. To be useful, the standard must have measurement uncertainty lower than the target uncertainty of the device under test.

The main challenges of defining differential pressure at high line pressure come from the very high ratio of the line pressure to the differential pressure. If, for example, the line pressure is 8 MPa (1 160 psi) and the differential pressure is 20 kPa (2.9 psi), the ratio is 400:1. In this case, obtaining differential pressure as the difference of two high pressure standards gives very poor results. In the example just given, defining 20 kPa (2.9 psi) differential by using two 8 MPa (1 160 psi) standards, even with very low uncertainty of ± 0.005 %, results in an uncertainty of 4 % on the 20 kPa differential. In addition, setting and stabilizing the pressure well enough so that a valid comparison of the standard and the device under test can be made can be difficult. The very best automated pressure controllers have control precision on the order of ± 10 ppm. Two of these controllers in an 8 MPa range will provide control precision of ± 0.8 % of a 20 kPa (1 160 psi) differential between them.

The exceptional precision of high performance piston gauges and special measurement methods can be used to define differential pressures at elevated line pressure with uncertainty much lower than the combined uncertainty on two independent high pressures.

PG7000 High Line Differential Mode supports the use of any two PG7102, PG7601, PG7202 gas operated piston gauges or any two PG7302 oil operated piston gauges in tandem to define differential pressures at high line pressures. PG7000's exceptional performance and advanced on-board measurement and processing capabilities are combined to improve the definition of differential pressure at elevated static pressure using two piston gauges and to make the operation simpler than with previous technology.

This technical note explains the principles of high line differential pressure mode, describes the operation and provides an uncertainty analysis for the differential pressures defined.

This revision updates uncertainties from the previous version and adds the 20 and 100 kPa/kg ranges recently introduced to the PG7601 and PG7102 platform. Also included in this revision are the uncertainties for the applicable piston-cylinder ranges for the PG7202 and PG7302 platforms. Though the uncertainties for the PG7302 are included, the hardware described in the high line differential mode schematic (see page 3) is not applicable to the PG7302 differential operation and only supports PG7202 operation up to 20 MPa (3 000 psi).

High line differential mode principle

The high line differential mode principle is to define differential pressure as the difference between the pressures defined by two piston gauges.

A crossfloating or "taring" procedure is used to cause the two piston gauges to define a common line pressure with precision much greater than the measurement uncertainty on either piston gauge. With this method, the only contribution of the line pressure to the uncertainty in differential pressure is the precision and short term repeatability of the piston gauges.

An independent gas piston gauge is connected to each side (low and high) of the differential device to be calibrated (see the high line differential mode schematic on page 3). The low side is designated the "tare" side (may be a PG7102, PG7202 or a PG7601). The only function of the tare side is to maintain a constant line pressure during the differential measurements. The tare piston is intentionally light so that it will float first when pressure is applied to the two pistons. The high side is designated the "reference" side (must be either a PG7202 or a PG7102). The reference maintains the line pressure and differential pressure is added to it. The pressure control system includes hardware to adjust pressure on either side independently and a bypass valve to isolate or connect together the two sides (low and high) of the system.

With the bypass valve open, the two piston gauges are loaded with mass corresponding to the line pressure. They are then crossfloated at the line pressure. Crossfloating consists of adjusting the mass load on the tare side so that both pistons float together, in equilibrium, at the common pressure. The definition of equilibrium is for both pistons to fall at their natural drop rate. If equilibrium is perfect, when the bypass valve is closed and each piston gauge defines an independent pressure, the differential pressure applied to the device under test is zero.

Once the bypass valve is closed, the mass corresponding to the desired differential pressure is loaded on the reference piston and the piston is refloated. The tare piston maintains the line pressure, the reference piston applies the line pressure plus the differential pressure.

The uncertainty on the differential pressure is made up of the random uncertainties associated with the original and on-going consistency of the line pressure between the two sides and the systematic uncertainties associated with the mass and piston cylinder effective area used to define the differential pressure. Note that exact value of the line pressure does not need to be known and is not significant in the uncertainty analysis. Only the consistency of the line pressure between the two sides is of concern.

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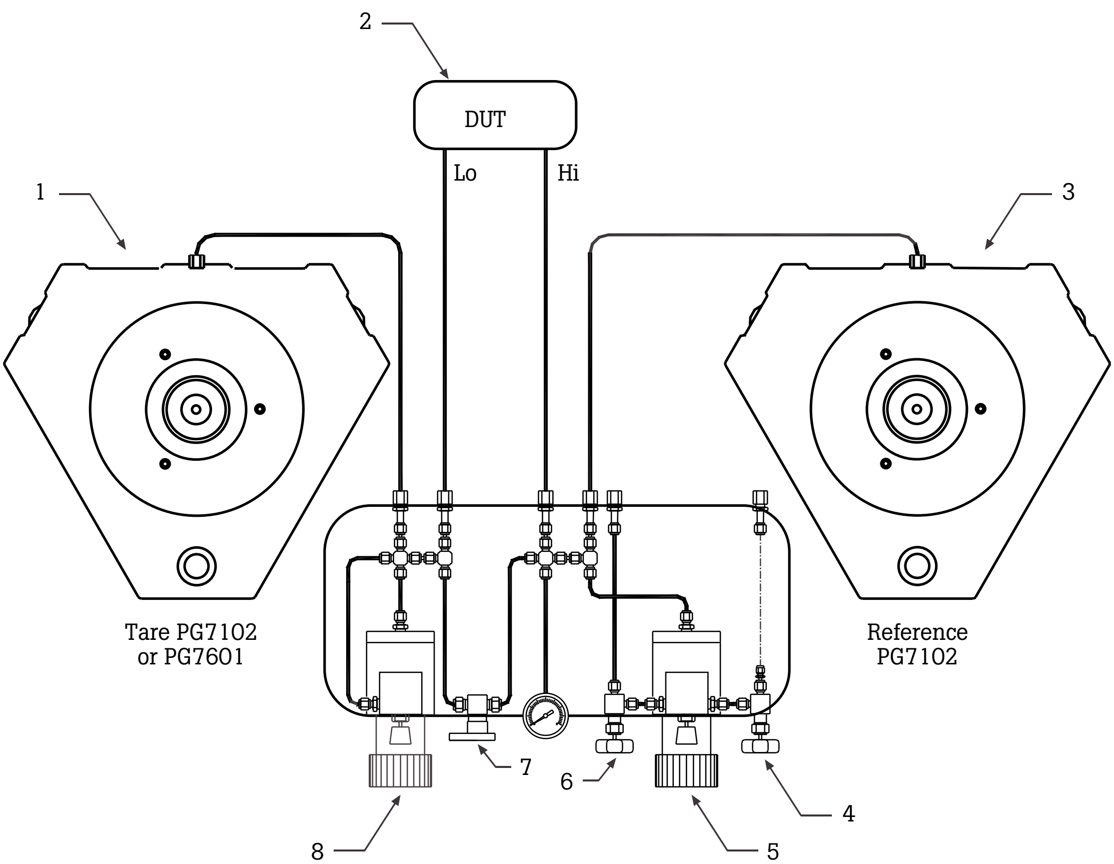
High line differential mode schematic



1. Tare PG7000
2. Differential Device Under Test (DUT)
3. Reference PG7102
4. MPC1-D INLET Valve
5. MPC1-D Hi Variable Volume (Hi VV)
6. MPC1-D VENT Valve
7. MPC1-D HI/LO BYPASS Valve
8. MPC1-D Lo Variable Volume (Lo VV)

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Differential mode operation

Differential mode operation can be selected directly on the PG7000 terminal in the same manner as gauge or absolute mode. PG7000's on-board integrated data acquisition and reduction capabilities are used to manage differential mode operation. The tare PG7000 is interfaced directly with the reference PG7000. The reference PG7000 becomes the "master" controlling all operation and the tare PG7000 is the "slave."

The MPC1-D manual pressure controller and PG7000 High Line Differential Mode Interconnections Kit provide the necessary interconnections, valving and pressure control for high line differential mode operation up to 20 MPa (2.9 psi) line pressure.

From a practical standpoint, differential mode operation is similar to operation in gauge mode but with the added task of monitoring and keeping the tare piston in floating position. In addition, a special crossfloating procedure is required each time a line pressure is set to minimize the differential pressure zero error due to the line pressure.

Differential pressure calculations

The reference PG7000 uses the calculations below to obtain differential pressure.

$$\Delta P_{HLD} = \frac{(M_R - M_{RX})g\left(1 - {\rho_a}/{\rho_m}\right)}{A_{\theta,P+\Delta P}} + P_L \left[(\alpha_{P_R} + \alpha_{C_R})(\theta_{RX} - \theta_R) - (\alpha_{P_T} + \alpha_{C_T})(\theta_{TX} - \theta_T)\right] + P_{HD})$$

$$A_{\theta,P+\lambda P} = A_{20,0} \cdot 10^{-6} \cdot \left[1 + (\theta_R - 20)(\alpha_{P_R} + \alpha_{C_R})\right]\left[1 + \lambda(P_L + \Delta P_{nom})\right]$$

$$P_L = P_{G_{RX}} = \left(\frac{(Mg\left(1 - {\rho_a}/{\rho_m}\right) + 2\pi\sqrt{{A_{\theta,P}}/{\pi}}\ \Gamma}{A_{\theta,P}} + P_{HG}\right)_{RX}$$

$$P_{HD} = -\left(\rho_{f_{P+\Delta P}} - \rho_{f_P}\right)gh_D + \left(\rho_{f_{P+\Delta P}} h_{P_R} - \rho_{f_{P+}} h_{P_T}\right)g$$

Uncertainty analysis

This uncertainty analysis assumes the use of a pair of nominally identical piston-cylinders in PG7000 piston gauges and that the PG7000 on-board high line differential mode support is used.

The uncertainty of a PG7000 in gauge mode is analyzed in the *"Uncertainty Analysis for Pressure Defined by a PG7601, PG7102, PG7202 or PG7302 Piston Gauge"* technical note.

The uncertainty in high line (HL) differential mode is different from the uncertainty in gauge mode primarily due to additional standard uncertainty components that must be expressed relative to the line pressure. This introduces a variable pressure term that is a third term in the typical pressure measurement uncertainties above. Also, some uncertainties listed in gauge mode are eliminated in HL differential mode due to the procedural step of crossfloating the piston-cylinders at the line pressure. The uncertainty on high line differential pressure definitions is the uncertainty in gauge mode modified by:

- **Elimination of the uncertainty on mass for the piston and mass carrying bell (see B1a and B1b of *"Uncertainty Analysis for Pressure Defined by a PG7601, PG7102, PG7202 or PG7303 Piston Gauge"* technical note.):** In HL differential mode, line pressure needs only be known to within ± 1 %. Since the line pressure is actually known to within the gauge mode standard accuracy specification the contribution of uncertainty in the mass load defining line pressure becomes insignificant. Note: This includes trim masses added to the tare piston during the crossfloating procedure.
- **Addition of uncertainties associated with trim mass loads:** Trim masses (masses of 50 g (1.8 oz) and less) have a higher uncertainty (± 1 mg per mass using a coverage factor of 2) than the rest of the masses used on PG7000 piston gauges. In gauge mode operation, the minimum mass load is 1 kg (35 oz) so the uncertainty associated with trim masses is relatively low compared to the overall mass load. In HL differential mode, mass loads well under 1 kg that include a combination of trim masses are often used to define differential pressure. In this case, the relative uncertainty of the trim masses may become significant. Since it is not possible to predict how many trim masses will be used in a specific test, this uncertainty analysis assumes a conservative number of nine trim masses used. These trim masses must be considered partially dependent because of the methods used to calibrate them. This uncertainty uses a correlation coefficient of 0.5 to calculate the standard uncertainty. The table below lists the piston-cylinder size, sensitivity to pressure, one standard uncertainty in mass and one standard uncertainty in pressure.

PG7601/PG7102

Piston-cylinder size	Sensitivity (Pa/mg)	1 std unc (mg)	1 std unc (Pa)
10 kPa/kg	0.010	5.4	0.054
20 kPa/kg	0.020	5.4	0.107
50 kPa/kg	0.050	5.4	0.268
100 kPa/kg	0.100	5.4	0.536
200 kPa/kg	0.200	5.4	1.07

PG7202/PG7302

Piston-cylinder size	Sensitivity (Pa/mg)	1 std unc (mg)	1 std unc (Pa)
100 kPa/kg	0.1	5.4	0.54
200 kPa/kg	0.2	5.4	1.08
500 kPa/kg	0.5	5.4	2.70
1 MPa/kg	1.0	5.4	5.4
2 MPa/kg	2.0	5.4	10.8

It is worthwhile to mention that this standard uncertainty is easily reduced. One method is to calibrate the trim masses with a lower uncertainty. Another, more practical choice, is to use nominal mass loads to reduce the number of trim masses used.

Type of uncertainty: Relative type B
Sensitivity: See table
Distribution: Normal
Standard uncertainty: See table

- **Change in definition of the uncertainty contributed from sensitivity (see B13 of the *"Uncertainty Analysis for Pressure Defined by a PG7601, PG7102, PG7202 or PG7303 Piston Gauge"* technical note.):** For HL differential mode this uncertainty is listed as a function of the line pressure. This is in addition to the relative uncertainty included for differential pressure. The uncertainty is identical to the uncertainty shown in the table for B13 but the relative portion of the uncertainty is multiplied by the line pressure. A standard uncertainty for sensitivity is included for both the tare and measuring piston-cylinders.

- **Addition of uncertainty due to the correction for the change in temperature of the pistoncylinder effective areas from time of crossfloat to the time a differential measurement is made:** When performing HL differential measurements the measuring and tare PG7000 is tared (nulled) by crossfloat at the line pressure. If, subsequently, the temperatures of the tare and reference piston-cylinders changes differentially, the result is a differential change in the line pressure which directly affects the differential pressure. PG7000's HL differential mode software corrects for the differential temperature changes real time but there an uncertainty associated with the correction. This uncertainty is relative to the line pressure. The full absolute uncertainty of the mounting post PRTs does not have to be considered because the correction is based on differential change in the piston-cylinder temperatures from the time of crossfloat (see B10 of 7920TN01A). The uncertainty contributed by the PRTs is only the performance characteristics of the PRTs, approximately ± 0.01 °C (32.02 °F) at k=2, and may be considered insignificant. However, the uncertainty in the piston-cylinder thermal expansion coefficients must also be considered. This uncertainty is considered once for differential pressure (see B16 of 7920TN01A), but is applied again to the line pressure. The uncertainty is slightly higher than B16 to account for the performance of the PRTs. The uncertainty, again, assumes a maximum correction of 1 °C (33.8 °F). The following table lists the piston-cylinder size, the thermal expansion coefficient for each piston-cylinder, one standard uncertainty and one standard uncertainty on pressure. A term is included for both the measuring and the tare piston-cylinder.

PG7601/PG7102/PG7202/PG7302

		1 std unc	
Piston-cylinder size	$(\alpha_p + \alpha_c)$ (°C^{-1})	1 std unc (°C^{-1})	1 std unc ppm
All sizes	9 x 10^{-6}	2.2 x 10^{-7}	0.3

Type of uncertainty: Relative type B
Sensitivity: 9 ppm/°C^{-1}
Distribution: Normal
Standard uncertainty: See table

- **Additional Type A uncertainty with respect to line pressure:** An additional uncertainty for the contribution of type A uncertainty based on the line pressure is needed to complete the uncertainty analysis. The type A uncertainty for differential pressure is already included as A1 in *"Uncertainty Analysis for Pressure Defined by a PG7601, PG7102, PG7202 or PG7303 Piston Gauge"* technical note. This type A uncertainty is to account for errors contributed from the initial tare when performing the crossfloat and any other additional random uncertainties contributed in a test. Experience has determined the worse case contribution to be ± 1 ppm, for k=2, for all gas operated piston-cylinder sizes, or, ± 2 ppm k=2, for oil operated piston-cylinder sizes, as long as there are no significant vibration or air drafts present. One standard uncertainty then becomes 0.5 or 1 ppm of line pressure.

Type of uncertainty: Relative type B
Sensitivity: 1 ppm/ppm
Distribution: Normal
Standard uncertainty: 0.5 or 1 ppm of LP

This uncertainty is dependent upon the specific conditions of the test and becomes more significant as line pressure increases. As mentioned earlier in this document, the errors contributed from this type A uncertainty may be reduced by averaging readings over a period of time.

Equipment required for PG7000 high line differential mode operation

Quantity	Equipment
2	PG7000 piston gauge platforms
1	Pair of gas or oil operated piston-cylinder modules of which one may be a "tare" pistoncylinder
1	Pair of mass sets of which one may be a "tare" mass set
1	MPC1-D-3000 or MPC1-D-1000 manual pressure controller (gas only)
1	PK-7100-MPCD-DIF, interconnections kit (gas only)

Specifications

Specifications assume the use of a pair of nominally identical piston-cylinders in two PG7000 piston gauges and that the PG7000 on-board high line differential mode support is used. PG7000s used in high line differential mode are extremely sensitive to environmental influences. To obtain the specifications below, the PG7000s must be installed on a surface that does not change level (as measured by the PG7000 bubble level) during operation and that is free from parasitic vibration.

There should be no air currents present that could interfere with the force applied by the mass loaded on the pistons (this includes air conditioner diffusers, fans and even the circulation of personnel moving about in the same room).

The dominant uncertainties in PG7000 high line differential mode are random uncertainties associated with the line pressure. These uncertainties can be reduced and in some cases eliminated by: a) integrating the output of the device under test for 20 to 30 seconds; b) observing the difference in the output of the device under test at true zero (bypass valve open) and PG7000 defined zero (bypass closed). This difference can be applied directly as a zero correction to all of the subsequent device under test differential readings.

Line pressure range
PG7202/PG7302 (applies to both if not indicated)
5 MPa/kg PG7302 piston-cylinders: 10 MPa to 500 MPa (1 500 to 72 000 psi)
2 MPa/kg PG7302 piston-cylinders: 4 MPa to 200 MPa (600 to 30 000 psi)
2 MPa/kg PG7202 piston-cylinders: 4 MPa to 110 MPa (600 to 16 000 psi)
1 MPa /kg piston-cylinders: 2 MPa to 100 MPa (300 to 15 000 psi)
500 kPa/kg piston-cylinders: 1 MPa to 50 MPa (150 to 7 500psi)
200 kPa/kg piston-cylinders: 400 kPa to 20000 kPa (60 to 3 000 psi)
100 kPa/kg piston-cylinders: 200 kPa to 10000 kPa (30 to 1 500 psi)
PG7601/PG7102
200 kPa/kg piston-cylinders: 400 kPa to 11 000 kPa (60 to 1 600 psi)
100 kPa/kg piston-cylinders: 200 kPa to 5 500 kPa (30 to 800 psi)
50 kPa /kg piston-cylinders: 100 kPa to 2 750 kPa (15 to 400 psi)
20 kPa/kg piston-cylinders: 40 kPa to 1 100 kPa (6 to 160 psi)
10 kPa/kg piston-cylinders: 20 kPa to 550 kPa (3 to 80 psi)

Differential pressure range
Differential pressure + line pressure < maximum line pressure

Measurement uncertainty
PG7302
5 MPa/kg piston-cylinders: ± [85 Pa + 2.1 ppm LP + (35 ppm + 0.04 ppm x LP) x DP]
2 MPa/kg piston-cylinders: ± [33 Pa + 2.1 ppm LP + (25 ppm + 0.04 ppm x LP) x DP]
1 MPa/kg piston-cylinders: ± (17 Pa + 2.1 ppm LP + 25 ppm x DP)
500 kPa/kg piston-cylinders: ± (8.3 Pa + 2.1 ppm LP + 18 ppm x DP)
200 kPa/kg piston-cylinders: ± (3.3 Pa + 2.1 ppm x LP + 20 ppm x DP)
100 kPa/kg piston-cylinders: ± (1.7 Pa + 2.1 ppm x LP + 20 ppm x DP) PG7202
2 MPa/kg piston-cylinders: ± [33 Pa + 1.3 ppm LP + (30 ppm + 0.15 ppm x LP) x DP]
1 MPa/kg piston-cylinders: ± [20 Pa + 1.3 ppm LP + (20 ppm + 0.15 ppm x LP) x DP]
500 kPa/kg piston-cylinders: ± [9 Pa + 1.3 ppm LP + (18 ppm + 0.15 ppm x LP) x DP]
200 kPa/kg piston-cylinders: ± (3.6 Pa + 1.3 ppm x LP + 20 ppm x DP)
100 kPa/kg piston-cylinders: ± (1.8 Pa + 1.3 ppm x LP + 20 ppm x DP)
PG7601/PG7102
200 kPa/kg piston-cylinders: ± (2 Pa + 1.3 ppm LP + 20 ppm DP)
100 kPa/kg piston-cylinders ± (1 Pa + 1.3 ppm LP + 20 ppm DP)
50 kPa/kg piston-cylinders: ± (0.50 Pa + 1.3 ppm LP + 14 ppm DP)
20 kPa/kg piston-cylinders: ± (0.23 Pa + 1.3 ppm LP + 14 ppm DP)
10 kPa/kg piston-cylinders (tungsten piston): ± (0.10 Pa + 1.3 ppm LP + 12 ppm DP)

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