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Calibration

Typical pressure measurement uncertainty defined by an FPG8601 Force Balanced Piston Gauge

2090TN05
Revised 2004 March 26

Technical Note

FPG8601 is a pressure standard designed to cover the range from less than 1 Pa to 15 kPa (0.00015 psi to 2.2 psi) gauge and absolute pressures. The instrument operates on the piston gauge principle. However, the force resulting from pressure on the piston is measured by a force balanced load cell rather than balanced against masses subjected to the acceleration due to gravity. For this reason, the measuring portion is designated a force balanced piston gauge (FPG)[1]. As of the date of the original of this technical note, FPG8601 has been used extensively in the Fluke Calibration metrology service calibration laboratory and several national measurement institutes[2].

This technical note is written to help metrologists understand the influences on measurement uncertainty when using an FPG8601. It is also a predictive uncertainty analysis for measured pressure based on worse case or typical influences, product specifications of system measurements and typical environmental conditions which are defined in the following sections. The document briefly describes the traceability of the FPG8601, ways to reduce uncertainty and some information on the special challenges of measuring low pressure precisely.

In providing specifications for the high performance fundamental pressure standards, Fluke Calibration has developed "typical pressure measurement uncertainty" specifications. These are intended to provide easy to use figures for overall uncertainty in pressure that can be applied with confidence by the typical user under typical operating conditions. They include all significant sources of uncertainty and are rounded to convenient values that can be used over each pressure range.

This document is intended to provide a detailed analysis of FPG8601 typical pressure measurement uncertainty specifications in each of its operating modes. The components that are included in the uncertainty, the sensitivities assigned to each component and how the components are combined into a global uncertainty in the defined pressure, are covered. The uncertainty analysis provides the FPG8601 user with a documented validation of typical uncertainty values. It can also be used to estimate the uncertainty that will be obtained if the uncertainty in one or more components is different from the typical values. The new component uncertainty values can be substituted and combined following the uncertainty analysis to arrive at a new value of overall uncertainty in pressure definition.

Limits and conditions

All uncertainties in this analysis are calculated using the methods described in ISO *"Guide to the Expression of Uncertainty in Measurement"*, June, 1992 (GUM) and ANSI/NCSL Z540-2-1997 *"The US Guide to the Expression of Uncertainty in Measurement"*[3].

Many of the uncertainties listed in this technical note are predicted Type B uncertainties that are also product specifications for the individual metrological components that make up the FPG8601. These uncertainties are used as limits of acceptance for the uncertainty of each component as they are tested by the Fluke Calibration metrology service. This ensures that the final combined and expanded uncertainty in pressure as defined by the FPG8601 can be realized with typical conditions and normal behavior of its on-board measurements.

Because some of the final uncertainties depend on the environmental conditions for which the FPG8601 is exposed this technical note defines these typical limits to be the following:

- Ambient temperature: 20 °C to 26 °C (68 °F to 78.8 °F)
- Change in Internal Temp: 0.2 °C/min (0.36 °F/min) with a total change of no more than 1 °C (1.8 °F) without rezeroing.

Note that ambient pressure and humidity are not included as limits. This is because the load cell and calibration mass are hermetically sealed from ambient conditions and are dependent upon the variance in the humidity and pressure of the piston-cylinder gap lubrication gas whose conditions are controlled.

Pressure calculations

The FPG8601 measures the difference in pressure between the high pressure chamber and the reference chamber [2]. The mode of operation depends on the condition of the reference chamber. These modes are:

- Gauge
- Absolute
- Absolute differential

In gauge mode the reference pressure is at or close to barometric pressure. In absolute and absolute differential the reference chamber is at a low residual absolute pressure that is measured by a high precision absolute capacitance diaphragm gauge. The calculated pressure as it is defined by an FPG8601 for Gauge (PG), Absolute Differential (P_{AD}), and Absolute (P_A) is calculated using the formulas to the right.

$$\Delta P = \frac{(K_{cal} \bullet \left(N + \delta N_1 + \delta N_2 + \delta N_3\right)}{A_{20}\left[1 + (\alpha_p + \alpha_c)(\theta - 20)\right]}$$

$$K_{cal} = g_L \bullet \left(1 - {}^{\rho_{LUB}}/_{\rho_M}\right) \bullet \left({}^{m_{cal}}/_{N_{cal}}\right)$$

$$P_G = \Delta P - (\rho_{high} - \rho_{low}) \bullet g_l \bullet H$$

$$P_{AD} = \Delta P - \rho_{high} \bullet g_l \bullet H$$

$$P_A = \Delta P + \rho_{ref} - \rho_{high} \bullet g_l \bullet H$$

And

$$\delta N1 = -K_b \bullet (\rho_{LUB} - \rho_{LUB0})$$

$$\delta N2 = K_d \bullet \left[(\rho_{LUB} - \rho_{ref}) - (\rho_{LUB0} - \rho_{ref0})\right]$$

$$\delta N3 = V \bullet g_l \left[\left({}^{P_{ref}}/_{T_{ref}}\right) - \left({}^{P_{ref0}}/_{T_{ref0}}\right)\right] \bullet {}^{M_W}/_{K_{cal}} \bullet Z_{gas} \text{ x } R$$

Where:

A_{20}	Effective area at 20 °C (m^2)
α_P	Thermal expansion piston (°C^{-1})
α_C	Thermal expansion cylinder (°C^{-1})
Θ	PC temperature (°C)
P_{ref}	Reference pressure (low chamber) (Pa)
ρ_{high}	Density high side (kg/m^3)
ρ_{low}	Density low side (ref) (kg/m^3)
H	Test to FPG ref height (m)
g_l	Local gravity (m/s^2)
N	Counts at a specific point (counts)
δN_1	Δ Air buoyancy correction (counts)
δN_2	Δ Drag correction (counts)
δN_3	Δ Reference pressure buoyancy correction (counts)
ρ_{LUB}	Density lubrication pressure (kg/m^3)
ρ_M	Density calibration mass (kg/m^3)
m_{cal}	Calibration mass value (kg)
N_{cal}	Number counts at time of balance calibration (counts)
P_{LUB}	Current lube pressure (Pa)
P_{LUB0}	Lube pressure at tare (Pa)
P_{ref}	Current ref pressure (Pa)
P_{ref0}	Ref pressure at tare (Pa)
T_{ref}	Gas temperature (K)
T_{ref0}	Gas temperature at Tare (K)
V	External volume of piston (m^3)
M_W	Test gas molecular weight (mol^{-1})
Z_{gas}	Test gas compressibility
R	Universal gas constant 8314.411 (J $kgmol^{-1}K^{-1}$)
Kb	Buoyancy coefficient (cnts/Pa)
Kd	Drag coefficient (cnts/Pa)

FPG8601 uncertainties

For each uncertainty component, an explanation of the variable or parameter is provided along with the value of one standard uncertainty, its sensitivity with pressure and the type of distribution associated with the uncertainty. These uncertainties may be calculated as relative to pressure or as a specific amount of pressure. After each of the uncertainty components has been considered, they are combined to provide a global, two part, relative and fixed value uncertainty for measurements made by the FPG8601 in each measurement mode. There are two of these combined uncertainty budgets:

- One for the low resolution
- One for the high resolution version of FPG8601

B1: Calibration mass (m)[kg]

The true mass value of the calibration mass t'hat is used for the day to day calibration the span of the load cell contributes to the uncertainty in pressure. The uncertainty of this mass, including a slight component for stability, is ± 5 x 10^{-6} x the mass value at a level of confidence of 95 %.

Type of uncertainty: Relative type B
Sensitivity: 1 ppm/ppm
Distribution: Normal
Standard uncertainty: 2.5 ppm

B2: Local gravity (gl)[m/s^2]

The value of local gravity and the uncertainty in that value cannot be provided with the FPG8601 since the knowledge of local gravity is specific to the location of use. However, it is well known that local gravity for most specific location in the United States can be obtained from the US Geodetic Survey with a typical uncertainty of ± 2 ppm with a coverage factor of 2.

Type of uncertainty: Relative type B
Sensitivity: 1 ppm/ppm
Distribution: Considered normal
Standard uncertainty: 1 ppm

B3: Lubrication air density (ρLUB)[kg/m^3]

The density of the gas that lubricates the FPG8601 piston-cylinder gap and surrounds the calibration mass and the load cell is calculated each time the FPG8601 updates the calculated pressure. Lubrication gas density is used with the calibration mass density, B4, to correct for air buoyancy as is shown in the differential pressure calculation equations. Either nitrogen or air can be used as the lubrication gas but the test medium must be the same. Lubrication gas density is a function of lubrication pressure, temperature and humidity. The uncertainty contributed by density is dependent upon the specifications of the sensors used to measure the conditions of the lubrication gas. Generally there are two nominal lubrication pressures. These are 40 kPa for absolute and absolute differential mode and 140 kPa for gauge mode.

The equation used for calculating lubrication gas density at temperature (T) and pressure (P) is:

$$\rho_{\text{lub e P,T}} = \frac{P \bullet M_W}{Z_{P,T} \bullet R \bullet T}$$

Where:

P	Lubrication gas pressure (Pa)
T	Lubrication gas temperature (measured in °C and added to Tn) (K)
$Z_{P,T}$	Compressibility of gas at P and T (-)
M_W	Molecular weight of gas (mole-1)
R	Universal Gas Constant (J kgmol-1 K-1)

The table below provides uncertainties in lubrication gas density resulting from the specifications of the on-board sensors used to measure ambient conditions (no uncertainty is necessary for R or M_W). There is an uncertainty due to the fact that lubrication gas has a controlled humidity but the density is not compensated for this humidity.

Measurement	**Uncertainty in measurement** (1 Std Unc)	**Uncertainty in gas density at 40 kPa** kg/m^3 (1 Std Unc)	**Uncertainty in gas density at 140 kPa** kg/m^3 (1 Std Unc)
Temperature	0.15 °C (0.27 °F)	0.0002 kg/m^3	0.0008 kg/m^3
Pressure	0.05 kPa (0.0073 psi)	0.0006 kg/m^3	0.0006 kg/m^3
Compressibility of gas at ambient pressure and temperature	0.1 %	0.0002 kg/m^3	0.0008 kg/m^3
Relative Humidity	+60 %	0.0027 kg/m^3	0.0020 kg/m^3
RSS combined		0.0028 kg/m^3	0.0024 kg/m^3

Root sum squaring the standard uncertainties in lubrication gas density provides a one standard uncertainty in lubrication gas density equal to 0.0028 kg/m^3 at 40 kPa and 0.0024 kg/m^3 at 140 kPa. For convenience only the larger value is used in this analysis.

Type of uncertainty: Relative type B
Sensitivity: 127 ppm/kg/m^3
Distribution: Considered normal
Standard uncertainty: 0.0028 kg/m^3

B4: Calibration mass density (ρM)[kg/m^3]

The density of the mass used to calibrate the span of the load cell must be known to account for the fluid buoyancy correction of the mass as it is surrounded by the lubrication gas. The uncertainty of the calibration mass density is approximately ± 2 % with a coverage factor of 2. Density is reported as being approximately 7 900 kg/m^3. 2 % of 7 900 (worse case) is 158 kg/m^3.

Type of uncertainty: Relative type B
Sensitivity: 0.026 ppm/kg/m^3 @ 140 kPa
0.007 ppm/kg/m^3 @ 40 kPa
Distribution: A priori rectangular
Standard uncertainty: 91 kg/m^3

B5: Fluid head height (h)[m]

In order to determine the contribution of uncertainty in a fluid head correction, a typical uncertainty in the height difference between the reference level of the FPG8601 and a test instrument needs to be chosen. Generally, the height can easily be measured ± 5 mm with a coverage factor of 2 using inexpensive apparatus available in most laboratories. The uncertainty in the density is based on perfect compressibility of the gas. This assumption is insignificant because the FPG8601 measures low pressures where compressibility is close to one.

Type of uncertainty: Relative type B
Sensitivity: 0.12 ppm/mm
Distribution: A priori rectangular
Standard uncertainty: 2.9 mm

B6: Medium Density (ρ_{high} - ρ_{low})[kg/m^3]

When considering the uncertainty in the medium density used to calculate head correction only the density of gas on the high side of the FPG8601 needs to be considered. This is because the low side density is subtracted from the high side density and the low side pressure is constant enough that its uncertainty can be disregarded.

Referencing the table in B3, lubrication gas density, the same equation is used for calculating medium density (without the uncertainty in humidity). The pressure is known to within the specifications of the FPG8601 pressure and compressibility is known to within ± 0.1 % using k=2. One standard uncertainty in gas medium then becomes dependent on the temperature of the medium. Once pressure measured by the FPG8601 is stable, it is assumed the gas temperature is stable and is equal to the FPG8601 internal temperature, ± 1 °C (1.8 °F) using k=2.

Measurement	**Uncertainty in measurement** (1 Std Unc)	**Uncertainty in medium density**
Temperature	0.17 %	0.17 %
Pressure	0.003 %	0.003 %*
Compressibility of gas at ambient pressure and temperature	0.005 %	0.005 %
Combined RSS		0.018 %

* Note that the uncertainty in pressure in the table above does not include the absolute part of the two part uncertainty of an FPG8601. Because the absolute part of the uncertainty in pressure dominates the total uncertainty at low pressure the contributions when applied to the uncertainty of density are insignificant.

The combined relative standard uncertainty in medium density is 0.18 % of the density calculated by the FPG8601. This uncertainty is calculated using a maximum typical head correction of one meter and assuming the density changes proportionally to the pressure over the full range of the FPG8601.

B7: Piston-cylinder temperature (θ)[°C]

The uncertainty in the prediction of the change of effective area with temperature is affected by the ability of the platinum resistance thermometers (PRT) in the FPG8601 mounting post to measure the piston-cylinder temperature and also uncertainty in that temperature.

The combined uncertainty in both these parameters is ± 0.1 °C (0.18 °F) with a coverage factor of 2.

Type of uncertainty: Relative type B
Sensitivity: 9 ppm/°C
Distribution: Considered normal
Standard uncertainty: 0.05 °C (0.09 °F)

B8: Verticality

The uncertainty in pressure calculated by the FPG8601 includes the deviation of verticality of the piston-cylinder axis relative to the direction of acceleration with gravity. The FPG8601 uses a precision bubble level adjusted to the piston-cylinder mounting post with an uncertainty of ± 2 minutes with a coverage factor of 2. Two minutes of non-verticality represents ± 0.19 ppm on pressure.

Type of uncertainty: Relative type B
Sensitivity: 1 ppm / ppm
Distribution: Asymmetrical
Standard uncertainty: 0.08 ppm

B9: Effective area (A_{20})[m^2]

The effective area of the FPG8601 piston-cylinder is determined using a PG7607 tungsten carbide, 5 kPa/kg, 50 mm diameter, piston-cylinder from the DHI Piston-Cylinder Pressure Calibration Chain. Because of the limitation of the lowest pressure of the 5 kPa/kg, defined by the mass of the piston and mass carrying bell, the crossfloat is performed from 5 kPa to 15 kPa. This appears to leave an untested range of effective area between 0 to 5 kPa (0 to 0.73 psi). However, the FPG8601 is zeroed before each effective area determination is made. Even though there is not an effective area determination at zero, the condition of the piston-cylinder is the same at zero differential pressure as the pressures between 5 kPa and 15 kPa and will influence the determinations made at those pressures.

Because of the type of crossfloat that is performed, the uncertainty contributed by the reference is the uncertainty in pressure, usually ± (10 ppm + 0.05 Pa) instead of the uncertainty in effective area, usually around ± 6 or 7 ppm. Another uncertainty in area to be considered is the possible difference in effective area between gauge and absolute modes. The effective area is only measured in gauge mode and is considered to be the same in absolute. An uncertainty is added to account for the possible difference in effective area in gauge and absolute modes.

Note: Though the effective area is not determined in absolute mode the FPG8601 is verified in both absolute and gauge mode over its entire range after complete characterization of all parameters.

Considering these aspects of the effective area determination the uncertainty is estimated to be 26 ppm using a coverage factor of 2. Because there is greater probability that the effective area is closer to what is determined than the boundaries of this uncertainty it is considered to be a normal distribution.

Type of uncertainty: Relative type B
Sensitivity: 1 ppm / ppm
Distribution: Considered normal
Standard uncertainty: 13 ppm

It should be noted that because the FPG8601 is a self contained system, i.e. non-interchangeable parts, the determination of effective area is done in such a way as to reduce or eliminate many errors, or uncertainties, contributed by other relative errors. For instance, if there is an unaccounted for 5 error in the calibration mass, then the final effective area will compense to account for this 5 ppm mass error. In order to maintain independence of the individual components in the FPG8601 its assumed other relative uncertainties are still fully accounted for and not assumed to be eliminated by the method of effective area determination.

B10a and b: Load cell precision

The design of the FPG8601 is such that the load cell is used to interpolate force measurement between two defined points, the calibration mass accelerated by gravity and when forces are equalized between the upper and lower chambers during zeroing. Because of this, the uncertainty in pressure defined by the FPG8601 is influenced by the precision of the load cell. Uncertainty in the load cell precision is described in two parts, relative and absolute, and accounts for the linearity and repeatability of the load cell. Because the FPG8601 is designed to be used with load cells that have different resolution there are two separate, two part specifications. These specifications are, using a coverage factor of 2:

Low resolution
(1 count = 1 mg or 10 mPa): ± (2 ppm + 2 counts)

High resolution
(1 count = 0.1 mg or 1 mPa): ± (2 ppm + 5 counts)

The load cell precision is a calibrated parameter and is best represented by a normal distribution.

Type of uncertainty: Relative and absolute type B
Sensitivity:
1 ppm/ppm and 10 mPa/count for low resolution
1 mPa/count for high resolution
Distribution: Considered normal
Standard uncertainty:
1 ppm + 1 count [10 mPa] for low resolution
1 ppm + 2.5 counts [2.5 mPa] for high resolution

Precision of the load cell, mainly repeatability, is dependent upon the frequency with which the load cell zero and span are calibrated. The precision uncertainties above do not consider a specific frequency of load cell calibration but can be easily maintained as long as the environmental conditions do not exceed the limits in the Limits And Conditions section and considering this function is automated and can be performed at any time.

B11: Elastic deformation

Though there is some theoretical elastic deformation of the FPG8601 piston-cylinder the forces experienced by the piston-cylinder are not large enough for this correction to be considered. Therefore there is not an uncertainty in elastic deformation included in this analysis.

B12: Thermal expansion ($\alpha p+\alpha c$)[°C^{-1}]

The effective area of an FPG8601 piston-cylinder changes with temperature depending on the thermal strain of the piston-cylinder materials. The magnitude of this change with temperature is the linear thermal expansion coefficient. The piston and cylinder are manufactured from tungsten carbide which has a thermal expansion of 4.5 x 10^{-6} °C^{-1} or 9.0 x 10^{-6} °C^{-1} for the full correction. This coefficient has an uncertainty of ± 5% with a coverage factor of 2.

Type of uncertainty: Relative type B
Sensitivity: 1.00/°C^{-1}
Distribution: Rectangular
Standard uncertainty: 2.6 x 10^{-7} °C^{-1}

B13: System stability

Though there are expected changes in the metrological values of effective area and mass, much of the influence of the change in FPG8601 measurements throughout a calibration interval will come from the changes of the system sensors and the change of the precision of the load cell. Mass, effective area and the system sensors have a predicted stability over 12 months built into their uncertainty or specification. This is not the case with the load cell precision and the zero stability of the residual pressure sensor in absolute mode. The uncertainty contributed from the zero drift of the residual pressure sensor is considered later in this analysis. To account for changes in linearity or repeatability of the load cell over a 12 month period a predicted uncertainty of ± 5 ppm may be used. Stability by itself is generally considered to be a rectangular distribution. This uncertainty can be checked and reduced based on the results of the check.

Type of uncertainty: Relative type B
Sensitivity: 1 ppm/ppm
Distribution: Rectangular
Standard uncertainty: 2.8 ppm

B14: Force corrections ($N + \delta N1 + \delta N2 + \delta N3$) [counts]

The output of the load cell in counts is corrected for three small influences depending on the mode of measurement. These coefficients correct for changes in force as system conditions change after the time of taring. These corrections, even when a maximum typical change is experienced, only cause a change of N of less than 1 count in low resolution and no more than 5 counts in high resolution. A conservative a priori estimate of ± 20% for these corrections leads to an uncertainty that is insignificant for both low and high resolution.

B15: Resolution

The standard uncertainty due to resolution is the resolution of either low and high resolution divided by the square root of 12. This leads to a value of 2.89 mPa for low resolution and 0.29 mPa for high resolution.

Type of uncertainty: Absolute type B
Sensitivity: 1 mPa/mPa
Distribution: Rectangular
Standard uncertainty:
Low resolution: 2.89 mPa
High resolution: 0.29 mPa

B16: Residual reference pressure (P_{ref}) [Pa]

When using the FPG8601 in absolute mode the residual pressure of the reference side is measured by a capacitance diaphragm gauge (CDG) and added to the calculated differential pressure. The uncertainty in this vacuum measurement must be included for absolute mode.

Typically, the residual pressure present in the reference side is less than 0.5 Pa. The CDG that is used to measure this pressure has an absolute range of 13 Pa (100 mTorr). Because the measurement is so low in the range of the CDG, the slope of the CDG is held to a specification of ± 0.5% of reading. Historical data has shown that the slope of these type of transducers are within ± 0.5% of reading for an interval much longer than 12 months. What is much more critical in terms of uncertainty in absolute mode is the zero drift of the CDG. For this reason the CDG is removable for zeroing with turbo-molecular vacuum pump and a very low vacuum sensor such as an ion gauge. When zeroed with sufficient frequency the zerodrift can typically be kept to a value of ± 3 mPa. The frequency of zeroing the CDG should be determined by the user of the instrument based on observed stability with frequent zeroing during the first few months of use. With use of the low resolution FPG8601, this specification may be expanded to ± 10 mPa to reduce the frequency of zeroing.

Considering the above, one standard uncertainty contributed by slope is 2.9 mPa, and for zero drift 1.7 mPa and 5.8 mPa for high and low resolution respectively.

Type of uncertainty: Absolute type B
Sensitivity: 1 mPa/mPa
Distribution: Rectangular
Standard uncertainty:
High resolution: 2.9 mPa and 1.7 mPa
Low resolution: 2.9 mPa and 5.8 mPa

Type A contribution

Because this uncertainty analysis covers a population of instruments, a specific Type A uncertainty cannot be assigned from a set of data. Generally, a Type A uncertainty will be determined when a customer uses the FPG8601 to calibrate another instrument to be used in the uncertainty analysis of that instrument. At the very lower pressure the FPG8601 measures, the type A component of uncertainty may be significantly affected by the hardware in the setup, local vibration and the pressure noise contributed by the pressure controller. FPG Tools software always calculates an average pressure output by the FPG8601 and, if automated, an average of the test output over a user specified interval. Both the average and standard deviation for each point of the reference and test output data are presented in the FPG Tools data file.

Since the value that is used for the FPG8601 output is an averaged value, and is usually for a set of data larger than 30 readings, it is preferable to use the standard deviation of the mean at each point to determine the Type A uncertainty.

Thermal transpiration

For a test device that operates at a temperature other than ambient and measures absolute pressure 10 Pa and below a thermal transpiration correction may need to be applied. This correction is a function of the difference in temperature between the test device and the FPG8601 and the internal diameter of the tubing where the temperature gradient is encountered [4].

The thermal transpiration correction is not linear and the significance depends on the pressure that is being measured. The equation used to correct for thermal transpiration may be referenced in the *FPG8601 Operation and Maintenance Manual* in the Calculations section.

An uncertainty of this correction as it applies to the test device is not given here because of the variability of the correction. For the residual pressure sensor on the FPG8601 reference chamber there is a thermal transpiration correction applied but an uncertainty need not be included because it is calibrated in the same conditions it is used and using the same thermal transpiration correction.

Combining uncertainties

The tables below list the uncertainties defined in the previous sections of this document for both resolution options and all three measurement modes. Individual uncertainties are categorized into relative or absolute uncertainties and listed as one standard uncertainty. The uncertainties are then combined by root sum squaring the individual uncertainties. Values shown in ppm or pressure (mPa) are combined separately. Finally, the relative and absolute combined uncertainty are each multiplied by a coverage factor of 2 and listed. Also, a typical pressure measurement uncertainty is assigned.

Note: If it is required to calculate a confidence level for 95 % for this uncertainty analysis, greater knowledge of the effective degrees of freedom for each standard uncertainty must be obtained. However, it should be noted that because all rectangular distributions are conservatively chosen and can be considered to have a high effective degree of freedom, and many of the dominant standard uncertainties are considered to have normal distributions, a coverage factor of 2 (k=2) should sufficiently approximate a confidence level of 95 %.

FPG8601 low resolution

Absolute mode typical pressure measurement uncertainty ± (25 mPa + 30 ppm)
Gauge and absolute differential mode typical pressure measurement Uncertainty ± (20 mPa + 30 ppm)

Variable or parameter	**Uncertainity ID**	**Gauge**	**Absolute differential**	**Absolute**
Full mass load		**1.5 kg**		
Relative uncertainties				
Cal Mass (M)	B1	2.50 ppm	2.50 ppm	2.50 ppm
Local G	B2	1.00 ppm	1.00 ppm	1.00 ppm
Air density (lube)	B3	0.36 ppm	0.36 ppm	0.36 ppm
Mass density	B4	2.37 ppm	0.67 ppm	0.67 ppm
Head (height)	B5	0.35 ppm	0.35 ppm	0.35 ppm
Head (density)	B6	0.22 ppm	0.22 ppm	0.22 ppm
PC Temperature	B7	0.45 ppm	0.45 ppm	0.45 ppm
Verticality	B8	0.08 ppm	0.08 ppm	0.08 ppm
Effective area	B9	13.00 ppm	13.00 ppm	13.00 ppm
Precision	B10a	1.00 ppm	1.00 ppm	1.00 ppm
Elastic deformation	B11	0.00 ppm	0.00 ppm	0.00 ppm
Thermal expansion	B12	0.26 ppm	0.26 ppm	0.26 ppm
System stability	B13	2.50 ppm	2.50 ppm	2.50 ppm
Combined		**13.8 ppm + 10.4 mPa**	**13.6 ppm + 10.4 mPa**	**13.6 ppm + 12.3 mPa**
Expanded to k=2		**28 ppm + 21 mPa**	**27 ppm + 21 mPa**	**27 ppm + 25 mPa**
Absolute uncertainties				
N	B14	0.00 mPa	0.00 mPa	0.00 mPa
dN_1	B14	0.00 mPa	0.00 mPa	0.00 mPa
dN_2	B14	0.00 mPa	0.00 mPa	0.00 mPa
dN_3	B14	0.00 mPa	0.00 mPa	0.00 mPa
Resolution (N)	B15	2.89 mPa	2.89 mPa	2.89 mPa
Vacuum (zero drift)	B16	0.00 mPa	0.00 mPa	5.80 mPa
Vacuum (slope)	B16	0.00 mPa	0.00 mPa	2.90 mPa
Precision (N)	B10b	10.00 mPa	10.00 mPa	10.00 mPa

FPG8601 high resolution

Absolute mode typical pressure measurement uncertainty ± (18 mPa + 30 ppm)
Gauge and absolute differential mode typical pressure measurement Uncertainty ± (5 mPa + 30 ppm)

Variable or parameter	**Uncertainity ID**	**Gauge**	**Absolute differential**	**Absolute**
Full mass load		**1.5 kg**		
Relative uncertainties				
Cal Mass (M)	B1	2.50 ppm	2.50 ppm	2.50 ppm
Local G	B2	1.00 ppm	1.00 ppm	1.00 ppm
Air density (lube)	B3	0.36 ppm	0.36 ppm	0.36 ppm
Mass density	B4	2.37 ppm	0.67 ppm	0.67 ppm
Head (height)	B5	0.35 ppm	0.35 ppm	0.35 ppm
Head (density)	B6	0.22 ppm	0.22 ppm	0.22 ppm
PC Temperature	B7	0.45 ppm	0.45 ppm	0.45 ppm
Verticality	B8	0.08 ppm	0.08 ppm	0.08 ppm
Effective area	B9	13.00 ppm	13.00 ppm	13.00 ppm
Precision	B10a	1.00 ppm	1.00 ppm	1.00 ppm
Elastic deformation	B11	0.00 ppm	0.00 ppm	0.00 ppm
Thermal expansion	B12	0.26 ppm	0.26 ppm	0.26 ppm
System stability	B13	2.80 ppm	2.80 ppm	2.80 ppm
Combined		**13.8 ppm + 2.5 mPa**	**13.6 ppm + 2.5 mPa**	**13.6 ppm + 4.2 mPa**
Expanded to k=2		**28 ppm + 5 mPa**	**27 ppm + 5 mPa**	**28 ppm + 8 mPa**
Absolute uncertainties				
N (see below)	B14	0.00 mPa	0.00 mPa	0.00 mPa
dN_1	B14	0.00 mPa	0.00 mPa	0.00 mPa
dN_2	B14	0.00 mPa	0.00 mPa	0.00 mPa
dN_3	B14	0.00 mPa	0.00 mPa	0.00 mPa
Resolution (N)	B15	0.29 mPa	0.29 mPa	0.29 mPa
Vacuum (zero drift)	B16	0.00 mPa	0.00 mPa	1.70 mPa
Vacuum (slope)	B16	0.00 mPa	0.00 mPa	2.90 mPa
Precision (N)	B10b	2.50 mPa	2.50 mPa	2.50 mPa

References

[1] P. Delajoud, M. Girard, "*A Forced Balance Piston Gauge for Very Low Gauge and Absolute Pressures*", August 2002

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Printed in U.S.A. 5/2012 4076198B_EN Pub-ID 11815-eng rev 01

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