New Breakthroughs In Digital Piston Gauge Technology

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Abstract

A new digital piston gauge technology covers absolute and gauge pressure ranges from a few Pa up to 25 MPa. Based on the dead-weight tester principle, the instrument uses a mass comparator to measure the force resulting from the pressure applied to a rotating piston/cylinder assembly. A special design of the measuring head allows an easy and quick change of the pressure range. The instrument has on-board environment monitoring facilities and is self-calibrating for long-term measurement stability. It offers highest level uncertainties to ± (0.5 Pa + 1.2 10^{-5} of reading) with resolution to 0.1 Pa.
This system can be totally automated by addition of an automatic pressure controller and calibration software for full automatic data acquisition. Used as reference or working standard this pressure standard is dedicated to the calibration of portable calibrators, pressure controllers, barometers or industrial level pressure balances.

1. Introduction

This presentation will focus on the technical principles of the digital piston gauge type pressure standard and explain the recent evolution of this technology.
Recent evaluation results will also be presented, demonstrating that digital piston gauge technology are acceptable as primary standards not only from the nature of the digital piston gauge, but also from its outstanding measurement specifications.

2. Primary standards versus transfer standards

One can say that without the existence of primary pressure standards, transfer standards such as gauges and electronic transmitters would be limited to detecting changes in pressure and repeating undefined and unstandardized values. It is by correlation with primary standards and exploitation of properties of repeatability that transfer standards become capable of making measurements having any accuracy in the absolute sense. This correlation is what is known as calibration.
Obviously then, the accuracy of a transfer standard is limited by the accuracy of the primary standard with which it is directly or indirectly calibrated and by its own metrological characteristics. More specifically, particularly now that linearity problems are easily corrected using microprocessors, it is the ability of a transfer standard to repeat identical

readings when confronted with identical situations that defines its accuracy. It is important for a user to know what factors affect the repeatability of a transfer standard, for it is from that information that calibration intervals ensuring the continuing accuracy of the transfer standard are determined. All transfer pressure standards rely upon the deformation of a material exposed to pressure to produce a measurable signal. The repeatability of the standard depends upon the stability of the mechanical characteristics of the material. Therefore, repeatability can be affected by such things as overpressures, long-term static pressure maintenance, alternating pressures, temperature cycling and physical changes which occur in materials and components over time.

Given the problem described above, one may wonder why transfer standards are used by those seeking accurate pressure measurements. Several obvious reasons immediately come to mind. First, for use in the real world, transfer standards currently offer much greater convenience. They allow quicker measurements, their outputs can be interfaced with data handling and control systems, they can be miniaturized and adapted to many different environments and, in general, they are less costly than primary standards. In addition, contemporary technology has produced transfer standards having truly remarkable metrological qualities so that highest accuracy can be achieved and maintained over relatively lengthy periods and under very demanding conditions.

However, by definition, no transfer standard can have the fundamental reliability over time of a primary standard. Every transfer pressure standard must be periodically calibrated by a direct or indirect comparison with a primary standard.

3. Using primary pressure standards

From the preceding discussion of the difference in nature between primary and transfer standards it follows that frequent reference to primary standards will enhance the accuracy and reliability of pressure measurement. It is the responsibility of the manufacturers of these instruments to make their use as convenient and versatile as possible. It is of equal importance that as little degradation in accuracy as possible occur between national standards and those produced for use at other levels.

In this spirit, some developments which have helped to simplify the use of pressure balances are :

(a) the use of masses whose values are round number multiples and sub-multiples of kilograms;
(b) improvements in piston-cylinder manufacturing techniques which allow adjustment of piston-cylinder effective surface area so that given mass values (kg) correspond to whole numbers of engineering pressure units (MPa);
(c) the development of completely interchangeable piston-cylinders and masses;
(d) the development of pistons of reduced surface area which require only small masses to reach high pressures;
(e) incorporation of all operating components into one transportable housing.

Despite these improvements pressure balances still present inconveniences and operational handicaps, for example :

(a) operation remains tedious as constant mass manipulation is necessary;
(b) risk of error and confusion in mass recording;
(c) the application of necessary corrections requires the use of fractional trim weights and computing capability;

(d) relative to some alternative systems use remains time-consuming and requires qualified personnel.

4. The force measurement aspect

The complaints focus mainly on mass or force measurement. In addition, remember that in overall accuracy the uncertainty in the force or mass measurement plays a relatively small role. For these reasons, recent efforts towards simplifying the use of primary pressure standards have concentrated on the force measurement aspect.

The piston-cylinder measuring element can be viewed as an extremely linear and repeatable analogue pressure-to-force transformer and researchers have speculated for some time that an alternative force measuring scheme might offer interesting possibilities. The component lacking has been a force-measuring instrument of metrological quality sufficient to make combination with a piston-cylinder a worthwhile project. For this reason, we have followed closely the developments in the force-measuring field and particularly in the area of precision digital balances.

The very large precision weight-measuring instrument market and progress in digital electronics as well as the incorporation of microprocessors has allowed balance manufacturers to introduce dynamometers whose linearity and repeatability are better than 1.10^{-5} of full scale. This development undeniably makes the combination of a piston-cylinder and an electronic dynamometer desirable for we have a force-measuring instrument whose accuracy compares favourably with the masses used traditionally. Now rather than loading a piston with mass (Figure 1), the masses can be used to check a dynamometer. When a piston is turned upside down and set on the dynamometer, the dynamometer will continuously interpolate force measurement (Figure 2).

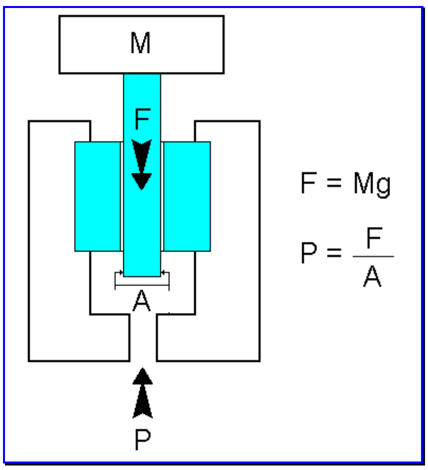

Figure 1. Principal of the pressure balance.

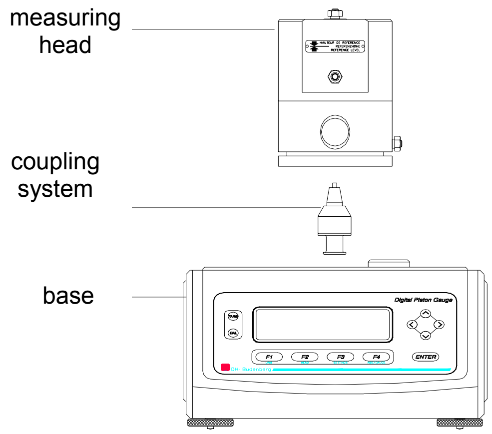

Figure 2. Principle of the digital piston gauge

5. The digital piston gauge primary pressure standard

5.1. Technical considerations

The remaining problem was to design and manufacture a satisfactory coupling system between the piston-cylinder and the dynamometer. We have made recent development in this field in order to improve the technique. This is a particularly delicate problem due to the fact that the piston must rotate in its cylinder to remain well centered and perfectly mobile. Rotation creates parasitic perturbations which must be perfectly filtered out. Another major problem is with defects in alignment between the piston and the dynamometer which cause variations in the point at which force is applied.

To solve these problems the following solutions were adopted (Figure 4 & 5).

(a) The rotation point was placed at the level of the piston head in order to achieve precise alignment with the piston axis.
(b) The pivot point takes the form of a tungsten carbide ball which acts directly on the end of the tungsten carbide piston. The centering of this ball relative to the axis of the piston is accomplished by a ball-bearing mounted on the piston head.
(c) A connecting rod mounted freely compensates for alignment defects between the axis of the piston and the measuring axis of the dynamometer which makes quick interchangeability of pistons possible.
(d) A system which combines a load limiting function and damping properties protects the dynamometer from overload due to overpressures, and eliminates residual vibrations created by piston rotation.
(e) Finally, selecting a piston rotation speed such as that one complete piston rotation occurs during one integration cycle of the dynamometer helps to ensure that the readout is perfectly stable and repeatable.

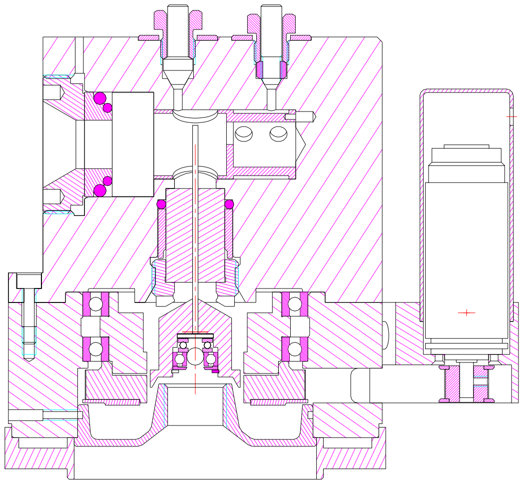

Figure 4. Section of digital piston gauge measuring head

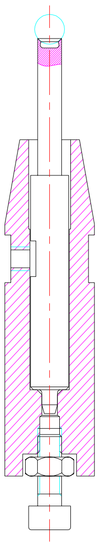

Figure 5. New designed coupling system

5.2 Metrological principle

The resulting pressure standard (Figure 6) has the characteristics required of a primary standard. The metrological elements which contributes to the overall accuracy of the system are those of a primary standard: (i) the piston-cylinders refers directly to absolute standards of length; (ii) the dynamometer is adjusted directly using master weights.
At any time the user can quickly check the performance of the dynamometer by removing the piston and its housing and using the set of masses supplied to verify linearity and full scale, and recalibrate if necessary.
Latest improvement in the field of dynamometers offer now the possibility to perform the dynamometer check without removing the piston-cylinder and its housing.

Figure 6. The digital piston gauge model DPG5

5.3 The auto-calibrating function

The dynamometer response to the force which is applied to it may drift with time. In addition to this drift which is due to the ageing of the dynamometer, a short-term drift may appear: this is an evolution of the dynamometer response according to the change of the environmental parameters, above all ambient temperature and relative humidity.

To curb these drifts, the DPG is fitted with an Auto-Calibrating Function (ACF) coupled with an Environment Monitoring Module (EMM).

The use of the ACF enables the dynamometer to easily free from this drift by readjusting its deviation according to the new environmental conditions, even when the measuring head is fitted.
The ACF consists in an automatic-loading internal standard mass which can be easily loaded by pressing a key located on the front panel, or from a remote computer. By applying the standard mass, you readjust the deviation of the dynamometer according to two points: zero and the mass-generated force value (i.e. the full scale value).

As mentioned before it is optionally possible to use a set of external standard masses in order to check the dynamometer linearity over 5 points. These masses can also be used to run an external calibration.

5.4 The environment monitoring module

In order to determine whether it is worthy to use the ACF, the DPG is equipped with an Environment Monitoring Module which consists in 3 sensors for ambient temperature, relative humidity and barometric pressure, and their electronic components.
When the ACF is in use, the environment conditions, for which the measurements carried out by the dynamometer are valid, are measured by the EMM and stored in the internal memory.

After the calibration, the EMM keeps on monitoring the evolution of the ambient conditions in real time.

If these conditions vary in proportions that might noticeably alter the measuring performance, the DPG displays a warning flag to advise the user to command the ACF in order to readjust the dynamometer to the new operating conditions. The warning flag is also sent to the command software if the DPG is operated from a remote computer.

Therefore, the EMM monitors the difference between the conditions stored during the calibration, at t_0, and the conditions measured when the operation took place, at t_{+1}. The sensors with which the EMM is fitted are not used for their accuracy and long-term stability, but for their short-term repeatability.

5.5 Pressure calculation

The equation for calculation of pressure using a digital piston manometer is derived from the equation of pressure of the pressure balance :

$$P = Kn \times \frac{N}{N_k} \times \frac{g_l}{g_n} \times \left(1 - \left(\lambda_{PC} \times P\right)\right) \times \left(1 - \alpha_{PC} \times \left(t - 20\right)\right) \times \left(\frac{\rho_{ac} - \rho_m}{\rho_{an} - \rho_m}\right)$$

where:

- P is the pressure measured by the digital piston manometer (Pa)
- Kn is the specific piston-cylinder assembly pressure to mass conversion coefficient issued from the calibration of the PCA.
- N is the dynamometer indication in counts
- N_k is sensitivity of the dynamometer
- g_l is the local acceleration of gravity in $m.s^{-2}$
- g_n is the normal acceleration of gravity in $m.s^{-2}$
- λ_{PC} is the piston-cylinder assembly pressure distortion coefficient (4,5 10^{-6}/°C)
- α_{PC} is the piston-cylinder assembly thermal dilation coefficient (4,5 10^{-6}/°C)
- t is the piston-cylinder assembly temperature in °C
- ρ_{ac} is the air mass density during the calibration in kg/m^3
- ρ_m is the calibration mass density in kg/m^3 (7920 kg/m^3)
- ρ_{an} is the air normal mass density in kg/m^3

The constant parameters entering in the computing of pressure are stored in the non-volatile memory of the DPG:

- piston-cylinder assembly Kn,
- sensitivity of the dynamometer (N_k),
- normal gravity (g_n),
- local gravity (g_l),
- piston-cylinder assembly pressure distortion coefficient (λ_{PC}),

- piston-cylinder assembly thermal dilation coefficient (α_{PC}),
- calibration mass density (ρ_m),
- air normal mass density (ρ_{an}).

Some of these parameters are particular to each piston-cylinder assembly and are determined during the calibration.
The variable parameters affecting the calculation of pressure are automatically measured and taken into account to calculate the pressure:

- piston-cylinder assembly temperature (t),
- air temperature,
- relative humidity,
- atmospheric pressure.

Pressure is automatically converted into any of the common pressure units and the user is also given the opportunity to configure the system for special units.

This rigorous metrology complies with the ISO TAG4 standard, and enables an ease of use as well as a speed of measurement operation.

6. Absolute pressure digital piston manometer

The instrument is designed so that both the bottom of the piston cylinder assembly and the dynamometer are located in a reference chamber (Figure 7).
When the reference chamber is evacuated, all pressure measurements are referenced to vacuum. If the chamber is opened to ambient pressure, the unit operates in gauge pressure mode.
A Pyrani vacuum gauge is built in the instrument in order to measure the residual pressure in the vacuum chamber. This is in the range 1 Pa to 10 Pa.
The pressure calculation equation for this unit is similar to (1) except that the residual pressure into the reference chamber (P vacuum) has to be taken into account :

$$P = Kn \times \frac{N}{N_k} \times \frac{g_l}{g_n} \times \left(1 - \left(\lambda_{PC} \times P\right)\right) \times \left(1 - \alpha_{PC} \times \left(t - 20\right)\right) \times \left(\frac{\rho_{ac} - \rho_m}{\rho_{an} - \rho_m}\right) + \text{Pvacuum}$$

Figure 7. The absolute pressure digital piston gauge model DPG8

7. Uncertainty budget

The table below is a summary of the uncertainty budget for a Digital Piston Gauge model DPG5. Calibration is performed via our COFRAC accredited pressure laboratory in France.

Typical error sources	Corresponding standard deviation	
Repeatability	$1.0\ 10^{-5}$ FS	
Kn (piston/cylinder effective area)	Piston area ≤ 5 bar/kg : $1.3\ 10^{-5}$ P Piston area > 5 bar/kg : $2\ 10^{-5}$ P	
Resolution	$0.1\ 10^{-5}$ FS	
Dynamometer calibration or Dynamometer linearity	$0.3\ 10^{-5}$ FS	
Hysteresis	$0.2\ 10^{-5}$ FS	
Air density	$0.04\ 10^{-5}$ P	
Gravity	Negligible	
PCA temperature	$0.08\ 10^{-5}$ P	
Coefficient de dilatation du PC	$0.03\ 10^{-5}$ P	
Temperature influence on the dynamometer	$0.2\ 10^{-5}$ P	
Liquid column	Negligible	
Global final uncertainty (k=1)	PCA ≤ 5 bar/kg : $1.1\ 10^{-5}$ FS + $1.3\ 10^{-5}$ P PCA > 5 bar/kg : $1.1\ 10^{-5}$ FS + $2.0\ 10^{-5}$ P	
Expanded uncertainty (k=2)	PCA ≤ 5 bar/kg : $2.2\ 10^{-5}$ FS + $2.6\ 10^{-5}$ P PCA > 5 bar/kg : $2.2\ 10^{-5}$ FS + $4.0\ 10^{-5}$ P	

All the DPG standards are delivered with a calibration certificate issued as standard by the COFRAC accredited DH·BUDENBERG's laboratory (accreditations 2-1033 and 2-1129), which assures the user that the presented calibration results are unbiased.

The COFRAC calibration guarantees the traceability of the measurements done by the DPG to the National French Standards and, through them, to the international standards.

The uncertainty calculation presented in the certificate respects the ISO TAG4 and EAL recommendations and shows the enlarged uncertainty of the DPG with a coefficient $k = 2$.
It takes into account the DPG's intrinsic measurement errors, the uncertainty of the reference means as well as the influence of the environment conditions.

The calibration is operated in accordance with the RM aero 802.22 recommendation and takes into account:
- the Kn specific coefficient determination
- the ACF calibration control

the pressure control of the DPG's metrological performances and the calculation of its measurement uncertainty by comparison with a reference standard enabling to apply a standard pressure comprised between $1.8\ 10^{-5}$ and $3.5\ 10^{-5}$ of the pressure according to the selected range

8. Conclusion

The combination of a piston-cylinder and an electronic dynamometer results in a primary standard that refers directly to the absolute standards that define pressure, mass, length, time, but which also offers the conveniences associated with transfer standards. The introduction of high resolution dynamometers combined with large surface area piston-cylinders assemblies has brought primary measurement specifications to the digital piston gauge.
By eliminating the tedious mass manipulating aspect, giving digital read-out and opening the possibility of interfacing with data handling systems, this instrument puts a primary standard at the disposition of many users who presently rely only upon transfer standards.
In many calibration facilities, transfer standards, which are all too rarely calibrated themselves, are routinely used. This tendency is due in part to the difficulties and high costs associated with the use of a primary standard.
The digital read-out primary standard is a positive step in making everyday calibrations more directly traceable to best pressure references and in diminishing the degradations in accuracy which are inherent in the use of a series of transfer standards.