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DEVELOPMENT OF 0,015 TO 2 BAR GAUGE PRESSURE STANDARD

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Abstract: This paper presents calibration system in the gauge pressure range of 0,015 bar to 2 bar developed in Laboratory for Process Measurement (LPM) at Faculty of Mechanical Engineering and Naval Architecture (FSB) in Zagreb. Design of the system, theoretical basis, main parameters influencing the effective pressure and the model for estimation of measurement uncertainty are described. The scope of the system is presented through pressure sensor calibration with results presented in tabular form.
Keywords: pressure, calibration, uncertainty estimation

1 INTRODUCTION

The Laboratory for Process Measurement at FSB Zagreb is developing and maintaining national pressure, temperature and humidity standards. The performance of those standards is adjusted to the ratio of available resources and the calibration needs in Croatia.

With quality assurance systems being introduced in ever increasing number of production plants and with growing number of testing and pressure calibration laboratories, the demand for traceable calibration of pressure sensors in Croatia is noticeably on the rise.

Besides the unavoidable industry required range of 1 bar to 600 bar for liquid filled gauge pressure instruments, the calibration in the bellow 2 bar gas gauge pressure range is second in demand. This is the consequence of multitude of process, pharmaceutical and food industry instruments and control systems (pressure flow, level) incorporating gauge and/or differential pressure sensors.

For this reasons the calibration standard in the gauge pressure range of 15 mbar to 2000 mbar as well as pertaining uncertainty calculations and test and calibration procedures are being developed at LPM.

2 THEORETICAL BASIS AND SYSTEM DESIGN

The theoretical basics are simple enough and well described in [1]. The essential element of the calibration system is a piston-cylinder (P/C) assembly. Calibrated weights having mass, M are loaded on the vertically positioned piston having effective area, A_e. The pressure to be calibrated/measured is applied to the base of the piston, creating an upward vertical force. This force is in equilibrium with the gravitational (downward) force F, due to loaded masses submitted to the local gravity g, and placed on the top of the piston (which is also a part of the load). When the rotating piston is freely floating the pressure in eq.(1) is generated.

$$p = \frac{F}{A_e} = \frac{M \cdot g}{A_e} \qquad (1)$$

But this definition simplicity is in practice marred by many influencing factors to be taken into account. They fall in two categories [2,3]:

- The quantities whose effect is independent of the applied pressure (zero pressure area of the standard P/C assembly, area temperature correction i.e. thermal expansion coefficients of piston and cylinder, local gravity, density of surrounding air, etc.). Note that those effects are also present at the minimum calibration pressure.

- The quantities whose effect varies with the amount by which the pressure is increased above the minimum calibration pressure (pressure distortion coefficient of standard, density of gas, load on standard, possibly density of load components.

Taking only main correction terms into account the applied pressure level is given by [2]:

$$p = \frac{\sum_i m_i g \left(1 - \frac{\rho_a}{\rho_{mi}}\right)}{A_0 \cdot (1 + \lambda \cdot p) \cdot \left[1 + \left(\alpha_p + \alpha_c\right)(t - 20)\right]} + \rho_{fl} \cdot g \cdot \Delta h \qquad (2)$$

where:

p	is the gauge pressure measured at the bottom of the piston,
m_i	is the individual mass value of each weight applied on the piston, including all floating elements
g	is the local gravity
ñ$_{a}$	is the density of air
ñ$_{mi}$	is the density of each weight
á$_{p}$	is the linear thermal expansion coefficient of the piston
á$_{c}$	is the linear thermal expansion coefficient of the cylinder
t	is the measured temperature of the piston-cylinder assembly during its use
A_0	is the effective area at null pressure
λ	is the pressure distortion coefficient
ñ$_{fl}$	is the density of the measuring fluid
Δh	is the difference in altitude between the reference level of the balance and the point where the pressure has to be measured

The schematic diagram of the pressure system designed to operate up to 2000 mbar is shown in Figure 1.:

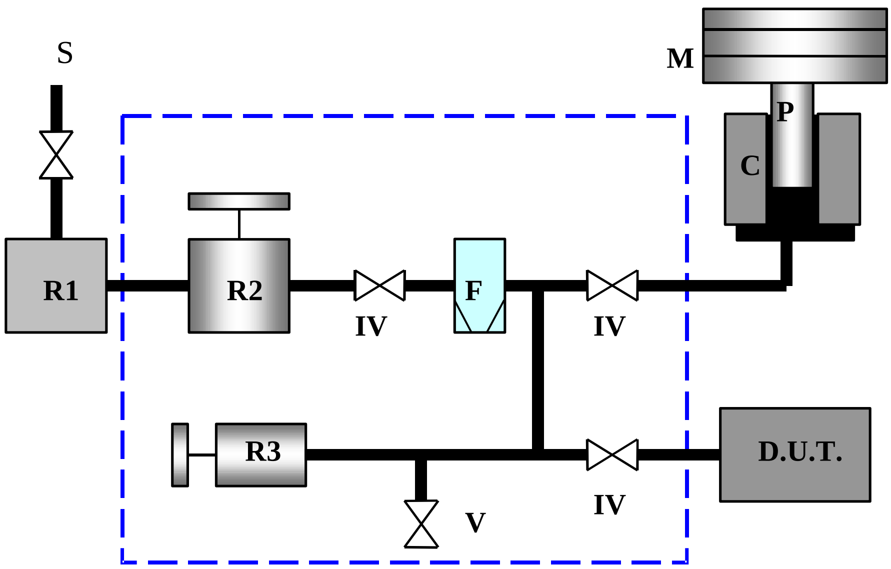

Figure 1. S – pressure source, R1 – pressure reducer, R2 – precision pressure regulator, F – microfilter, M – masses, P – piston, C – cylinder, D.U.T. – device under test, V –bleed off valve, R3 – variable volume, IV – isolation valves

The gas used in the system (Figure 1) is nitrogen. The pressure of nitrogen from the source S, is reduced roughly from app. 200 bar to app. 7 to 10 bar (R1) and then to closely above the desired nominal pressure. Through the isolation valve IV the nitrogen is led to the filter. Although nitrogen of 99.999% purity is used, 10 µm filter F, installed upstream from the P/C assembly, removes water and oil droplets as well as dirt particles that might penetrate the system. The calibration pressure in the system is determined by the ceramic piston and metal cylinder assembly P/C (ordered from manufacturer “Pressurements”). The effective area is, through manufacturer’s standards, traceable to NPL and is calibrated to the effective area uncertainty of ±100 ppm. The minimum calibration pressure is limited by the piston weight and effective area ratio which, for this system, amounts to 15 mbar.

In most calibration applications it is important to ensure that the pressure is held as stable as possible. To satisfy that condition, different pressure regulator settings (R1, R2, R3, Figure1.) and exhaust valve, V, can be simultaneously combined.

The operation of the system can be establish in two modes (the open and the closed mode). In the open mode the nitrogen flows through system exiting through the bleed off valve. In the closed mode the bleed of valve V is closed, and the system pressure is adjusted by the variable volume device R3. In both modes the continuous P/C unit and device under test (DUT) leakages must be finely compensated for in order to keep the system stability and the piston fall rate at the desired levels.

3 ESTIMATION OF UNCERTAINTIES AND CALIBRATION RESULTS

3.1 Uncertainty estimation

The way the uncertainties are estimated is dependent on the type of the device under test (DUT). In this example the calibration of pressure gauges with elastic sensing elements is considered. In such case uncertainty budget can be estimated in the following way, [4,5]:

Combined standard uncertainty, u, is calculated from the equation (3):

$$u^2 = u_{PC}{}^2 + u_{Corr}{}^2 + u_{cm}{}^2 + u_r{}^2 + u_{f_0}{}^2 + u_b{}^2 + u_h{}^2 \qquad (3)$$

where, u_{PC} -P/C unit uncertainty taken from manufacturer's calibration report
u_{Corr}: -P/C unit uncertainties under conditions of calibration
u_{cm}: -calibration method uncertainty
u_r: -resolution uncertainty caused by DUT
u_{fo}: -zero deviation uncertainty (DUT)
u_b: -repeatability uncertainty (DUT)
u_h: -hysteresis uncertainty (DUT)

Sources of uncertainty are divided in three groups: pressure standard (P/C unit), calibration method and DUT.

Uncertainties u_{PC} and u_{Corr} pertain to pressure standard.
U_{PC} are always based on specific calibration report. In our case distortion coefficient, λ, is practically zero which is the consequence of relatively low gauge pressure range (less than 2 bar) and it’s rigid ceramic material.

P/C unit uncertainties under conditions of calibration, u_{Corr}, are calculated from partial derivatives (sensitivities) of eq.(2) to temperature (t), thermal expansion coefficients ($\alpha_p+\alpha_c$), and local gravity (g) (Table 4.).

$$u_{Corr}{}^2 = \sum_i \left(\frac{\partial p_e}{\partial X_i}\right)^2 \cdot u_{Xi}{}^2 = \left(\frac{\partial p_e}{\partial t}\right)^2 \cdot u_t{}^2 + \left(\frac{\partial p_e}{\partial \alpha}\right)^2 \cdot u_\alpha{}^2 + \left(\frac{\partial p_e}{\partial g}\right)^2 \cdot u_g{}^2 \qquad (4)$$

Uncertainty u_{cm} generally pertains to calibration method and can include: static pressure differences (differences in height of reference levels of standard and DUT), in transducer calibration possible influence of amplifiers, frequency meters, voltmeters (not applicable in this case), etc.

Uncertainties u_r, u_{fo}, u_b and u_h pertain to DUT and they are all evaluated the same way, i.e. assuming rectangular distribution of their limiting values.

$$u_i = \sqrt{\frac{1}{3}\cdot\left[\frac{(a_{+i} - a_{-i})}{2}\right]^2} = \sqrt{\frac{1}{3}\cdot a_i^2} \qquad (5)$$

The expanded uncertainty, U, is directly derived from the combined standard uncertainty by multiplying it with a coverage factor *k*=2.

3.2 Calibration results

Results are given for specific Bourdon tube gauge with uncertainties estimated as above. Calibration is performed on test system (Figure 1.) in the open mode and the calibration results are presented in Tables 1. and 2. which summarise results for all calibration points. Regarding the accuracy class of DUT (in this case 0.1 % FS and 0,001 bar resolution) calibration points are selected in advance according to [5] spanning the full scale of 1000 mbar. Nominal pressure for each point (which pertains to standard conditions) is first corrected to actual calibration conditions according to eq.(2) to obtain effective (corrected) pressure p_e. Calibration is performed in three measuring sequences: M1 (ascending), M2 (descending), M3 (ascending) [5], and arithmetic mean value M is calculated.

Table 1. Calibration results (part one)

No.	Nominal pressure (standard)	Corrected pressure (standard)	Reading (DUT)			Mean value M
	p mbar	p_e mbar	M1 mbar	M2 mbar	M3 mbar	((M1+M3)/2+M2)/2 mbar
1	0	0.000	0.00	0.00	0.00	0.00
2	100	99.893	100.00	100.00	100.00	100.00
3	200	199.785	200.00	200.00	200.00	200.00
4	300	299.678	300.20	300.50	300.20	300.35
5	400	399.570	400.20	400.50	400.50	400.43
6	500	499.462	499.50	500.00	500.00	499.88
7	600	599.355	599.50	600.00	600.00	599.88
8	700	699.248	699.50	700.00	699.50	699.75
9	800	799.140	799.50	800.00	799.50	799.75
10	900	899.033	899.50	899.80	899.80	899.73
11	1000	998.925	999.50	999.50	999.50	999.50

Deviation (Table 2.) is calculated as difference between arithmetic mean value, M, and effective pressure, p_e. Repeatability is difference between two ascending measuring lines (M3-M1), and hysteresis is difference between ascending and descending measuring lines (M2-M1). Expanded uncertainty, U, for all measuring points are given in last column (Table 2.).

Table 2. Calibration results (part two)

No.	Corrected pressure (standard) p_e mbar	Mean value M mbar	Deviation M-p_e mbar	Repeatability M3-M1 mbar	Hysteresis M2-M1 mbar	Uncertainty U mbar
1	0.000	0.00	0.00	0.00	0.00	0.12
2	99.893	100.00	0.11	0.00	0.00	0.13
3	199.785	200.00	0.22	0.00	0.00	0.14
4	299.678	300.35	0.67	0.00	0.30	0.23
5	399.570	400.43	0.86	0.30	0.30	0.30
6	499.462	499.88	0.41	0.50	0.50	0.45
7	599.355	599.88	0.52	0.50	0.50	0.46
8	699.248	699.75	0.50	0.00	0.50	0.37
9	799.140	799.75	0.61	0.00	0.50	0.39
10	899.033	899.73	0.69	0.30	0.30	0.37
11	998.925	999.50	0.57	0.00	0.00	0.31

Uncertainty must be calculated for each calibration point separately. Without loss of generality we proceed with complete results of uncertainty estimation for one calibration point: p_e=599.36 mbar, expanded uncertainty U=0,46 mbar (shadow highlighted row, Table 2.) with details given in Tables 3. and 4.

Table 3. Uncertainty evaluation for one measuring point (599.88 mbar)

Source of uncertainty	Relation	Numerical value mbar	Factor	u^2 mbar
Pressure Standard:				
P/C unit	$2.5 \cdot 10^{-4} \cdot p_e$	0.1498	½	u_{PC}^2 0.0056
P/C unit under conditions of calibration	Table 4 (U_{Corr})	0,00546	½	u_{Corr}^2 0.0027
Calibration Method:				
Difference in height of reference levels	Neglected	0.0	$1/\sqrt{3}$	u_{cm}^2 0.0000
DUT:				
Resolution r	1/10*r	0.1	$1/\sqrt{3}$	u_r^2 0.0030
Zero deviation f_o	$f_o/2$	0.0	$1/\sqrt{3}$	u_{fo}^2 0.0000
Repeatability b	b/2	0.25	$1/\sqrt{3}$	u_b^2 0.0208
Hysteresis h	h/2	0.25	$1/\sqrt{3}$	u_h^2 0.0208
				Σu^2= 0.0533

Expanded uncertainty $U = k A \sqrt{\Sigma u^2} = 0.46$ mbar (with k=2)

Table 4. P/C unit uncertainties under conditions of calibration for one measuring point (599.88 mbar)

Influence quantity	Value	Unit	Limiting value	Standard Deviation	Sensitivity Coefficient $(Mp_e/Mx_i)\cdot p_e$	Numerical Value of Sensitivity Coefficient	Contribution to the Standard Uncertainty
Area Temp. Correction	22.00	°C	0.50	0,2887	$(á_p+á_c)\cdot p_e$	0.00539415	u_t=0.001557
Thermal Exp. Coeff. Std.	9.00E-06	$°C^{-1}$	1.00E-06	5.77E-07	$(t_k-t_o)\cdot p_e$	2397.4	$u_á$=0.001384
Local Gravity	9.80621	m/s^2	5.00E-05	2.89E-05	p_e/g	61.1194335	u_g=0.001764
						U_{Corr}=	0,0054601

Where U_{Corr} is calculated as:

$$U_{Corr} = k \cdot \sqrt{u_t^2 + u_\alpha^2 + u_g^2} \tag{6}$$

5 CONCLUSION

The design and performance of pressure standard in the gauge pressure range of 15 mbar to 2000 mbar, developed in Laboratory for Process Measurement at FSB Zagreb has been presented. It's development has been spurred by ever increasing demand from industry for traceable calibration in that pressure range.

The system is based on ceramic piston and metal cylinder assembly and custom designed pressure control and supply system filled with nitrogen which can operate in open or closed mode.

The minimum calibration pressure is limited by the piston weight and effective area ratio which amounts to 15 mbar. It can be used for cross floating of deadweight pressure gauges and for calibration of all types of pressure sensors and transducers. The overall uncertainty in the generated pressure, which also includes conditions of calibration influences, is estimated to be around ± 0.025 % of reading.

The analysis of uncertainties is given for the case of Bourdon tube dial gauge calibration. The estimation of uncertainties includes relevant contributions of the standard, of the method and of the device under test. From the results given in tabular form it can be seen that, in case of elastic element sensors, the main contribution to the overall uncertainty is the device under test itself. Further more the contributions of the standard and of the method are not only lower but also more predictable (known nature, controlled environment in the laboratory, etc.) while the contribution of the DUT can only be assessed by post calibration analysis of hysteresis and repeatability data. This can be clearly seen in the calibration example results where the governing uncertainty contributor appears to be (Table 2., No. 7) repeatability (0,5 mbar) of DUT.

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