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Calibration of Pressure Gauges

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Abstract: The aim of this work is to verify and calibrate a mechanical Bourdon-tube pressure gauge for which the manufacturer provides only basic specifications. Before such instruments are integrated into industrial or laboratory systems, additional information about their behaviour—such as linearity, systematic error, hysteresis, and measurement uncertainty—is required to ensure reliable operation and compliance with metrological standards. This paper presents a practical methodology for the rapid identification of the key metrological parameters of a pressure gauge. The procedure uses a pneumatic pressure source and a high-accuracy reference gauge to compare the indicated and reference pressures over a defined range during increasing and decreasing pressure cycles. The method enables the evaluation of accuracy, repeatability, and stability, and includes an uncertainty assessment based on the GUM approach. The presented methodology is suitable for input inspection and routine verification, providing a reliable basis for determining whether a pressure gauge is appropriate for its intended application.

Keywords: pressure gauge calibration; Bourdon tube; systematic error; measurement uncertainty; linearity; hysteresis.

1. Introduction

Pressure gauges represent essential measurement instruments in a wide range of industrial, laboratory, and technological processes. They serve as primary devices for monitoring operating conditions, ensuring process stability, and maintaining safety in systems involving fluids and gases [1–3]. Among the various types of pressure-measuring instruments, Bourdon-tube gauges remain the most widely used due to their mechanical simplicity, robustness, and reliability in both industrial and laboratory environments [1, 4]. Their operational principle is based on the elastic deformation of a curved metallic tube under pressure, which provides a stable and repeatable response across a broad measuring range.

Because pressure gauges are often employed in safety-critical applications—such as hydraulic systems, compressed-air networks, process engineering, and energy production—their accuracy and long-term stability are of great importance. Mechanical gauges are subject to material fatigue, mechanical wear, temperature effects, and vibration, all of which may gradually degrade their performance. For this reason, standards and regulatory bodies require that pressure gauges undergo regular inspection, verification, and calibration to ensure that their measurement error remains within the allowable limits [5–7]. European standard EN 837-1 explicitly defines construction requirements, accuracy classes, maximum permissible errors (MPE), and performance criteria for Bourdon-tube pressure gauges [4]. In addition, calibration procedures must comply with the metrological principles of ISO/IEC 17025, which defines requirements for competence and traceability in calibration laboratories [6].

Calibration provides a systematic method for evaluating the accuracy, linearity, hysteresis, and repeatability of a pressure gauge by comparing its indication with a reference instrument of higher accuracy. Through this process, it is possible to quantify

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the systematic error, detect potential mechanical degradation, and estimate the measurement uncertainty according to internationally accepted guidelines such as the GUM framework [7, 8]. Reliable calibration is therefore crucial not only for meeting legal and normative obligations, but also for ensuring the consistent and safe operation of industrial systems.

The main objective of this article is to experimentally evaluate the metrological performance of a Bourdon-tube pressure gauge of accuracy class 1.0. The study focuses on determining its systematic error, linearity, hysteresis, and overall measurement uncertainty using a pneumatic calibration setup with a high-precision digital reference gauge. The results provide a detailed assessment of the gauge's accuracy and suitability for continued operational use, while also demonstrating a complete calibration methodology applicable in practical engineering practice.

2. Experimental Materials and Methods

For the verification of measurement accuracy, an analogue Bourdon-tube pressure gauge (Figure 1) with accuracy class 1.0, compliant with EN 837-1, was selected. The gauge has a nominal measurement range up to 1.6 MPa and is based on elastic deformation of the Bourdon spring, making it suitable for comparative calibration procedures.

Figure 1: Verification pressure gauge.

A handheld pneumatic pressure test pump Additel 914 (Figure 2) was used as the pressure generation device. This manually operated pump enables pressure control within a range from 95% vacuum to 375 psi (25 bar). Fine pressure adjustment is provided by a precision screw press, allowing incremental changes with a resolution of approximately 10 Pa (0.1 mbar). The test pump serves exclusively as a pressure source and enables the simultaneous connection of two instruments: the reference pressure gauge and the pressure gauge under test.

Figure 2: Pressure test pump Additel 914.

As the reference standard, the digital pressure gauge Additel 681 (Figure 3) was employed. This microprocessor-based pressure reference gauge offers both analogue and digital readouts. Its measurement range extends to 20 MPa, and the manufacturer specifies a maximum permissible error (MPE) of ±0.02% of the nominal value, ensuring that it meets the accuracy requirements for reference-grade calibration.

Figure 3: Reference pressure gauge Additel 681.

The pressure gauge under test and the reference gauge were connected in parallel to the pneumatic pressure test pump (Figure 4). The calibration procedure consisted of gradually increasing the applied pressure to predetermined calibration points of 0.2 MPa, 0.4 MPa, 0.6 MPa, 0.8 MPa, 1.0 MPa, 1.2 MPa, and 1.4 MPa. At each point, readings from both the tested gauge and the reference gauge were recorded. After reaching the maximum pressure of 1.4 MPa, the pressure was slowly decreased, and the same measurement points were recorded during the descending cycle. This allowed the evaluation of hysteresis, stability, and potential mechanical friction effects within the Bourdon tube mechanism.

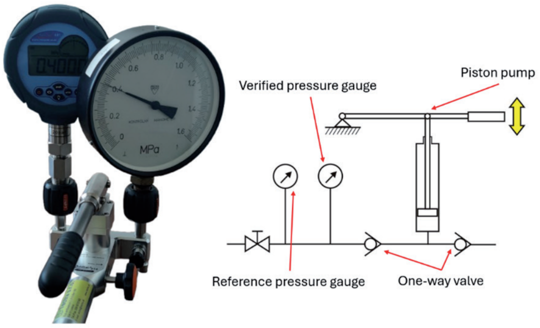

Figure 4: Schematic diagram of the measuring chain

The complete ascending and descending pressure cycle was repeated ten times, enabling the assessment of the repeatability, short-term measurement stability, and potential drift of the tested pressure gauge.

3. Calibration Results and Metrological Evaluation

A total of ten measurement cycles were performed for both the increasing (ascending) and decreasing (descending) pressure sequences. At each predefined calibration point (0.2–1.4 MPa), the indication of the tested pressure gauge and the reference pressure gauge were recorded. Table 1summarises the mean values obtained from the ten repeated measurements for both the increasing and decreasing pressure sequences.

Table 1: Mean values of the measured pressure indications during increasing and decreasing pressure cycles.

Reference pressure (MPa)	Pressure increasing - average (MPa)	Pressure reduction - average (MPa)
0.2	0.204	0.202
0.4	0.405	0.406
0.6	0.604	0.605
0.8	0.805	0.803
1.0	1.008	1.008
1.2	1.205	1.203
1.4	1.400	1.400

Table 2presents the calculated systematic errors of the tested pressure gauge at each calibration point. For each measurement point, the systematic error Δp_{sys} was evaluated according to:

$$\Delta p_{\text{sys}} = p_{\text{ind}} - p_{\text{ref}}, \qquad (1)$$

where p_{ind} – value indicated by the tested pressure gauge, p_{ref} – value indicated by the reference pressure gauge (Additel 681).

A positive systematic error therefore indicates that the tested gauge overestimates the applied pressure, whereas a negative error would indicate an underestimation.

Table 2: Systematic errors obtained for both ascending and descending pressure cycles.

Reference pressure (MPa)	Pressure increasing - systematic error (MPa)	Pressure reduction - systematic error (MPa)
0.2	0.004	0.002
0.4	0.005	0.006
0.6	0.003	0.005
0.8	0.004	0.002
1.0	0.007	0.008
1.2	0.004	0.003
1.4	0.000	0.000

The results indicate that the systematic error remains within a narrow interval across the full measurement range, with values typically within 0.002–0.008 MPa. The largest deviation during pressure increase occurs at 1.0 MPa, where the tested gauge overestimates the pressure by 0.007 MPa. A similar behaviour is observed during pressure reduction, with a maximum error of 0.008 MPa at the same pressure level.

The comparison of increasing and decreasing pressure sequences reveals only minor differences, which suggests low hysteresis of the mechanical Bourdon-tube mechanism. The reduction cycle occasionally shows slightly higher deviations (e.g., at 0.4 MPa and 1.0 MPa), but the overall differences between the two sequences remain small. At the upper limit of the tested range (1.4 MPa), the systematic error approaches zero in both cases, indicating good linearity at full-scale pressure.

These results confirm that the tested pressure gauge exhibits stable and repeatable behaviour over the measured range, with systematic errors well aligned with expectations for instruments of accuracy class 1.0.

The measured data obtained during the increasing and decreasing pressure sequences were graphically represented as the dependence of the reference pressure on the average indicated pressure of the tested pressure gauge. For each dataset, a linear trend line was fitted to approximate the relationship between the applied reference pressure and the measured indication.

The trend line is described by the standard linear regression equation:

$$p_{\mathrm{ind}} = a \cdot p_{\mathrm{ref}} + b, \tag{2}$$

where a – slope of the regression line, b – intercept of the regression line.

Based on the measured data, the following regression equations were derived:

Pressure increasing:

$$p_{\mathrm{ind}} = 0.9987 \cdot p_{\mathrm{ref}} + 0.0051, \tag{2.1}$$

Pressure reduction:

$$p_{\mathrm{ind}} = 0.9987 \cdot p_{\mathrm{ref}} + 0.0045, \tag{2.2}$$

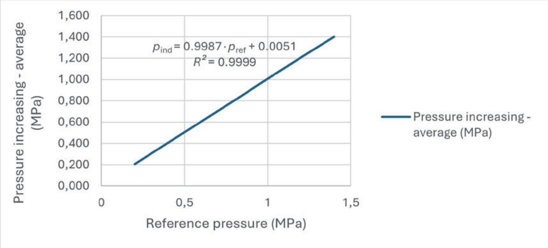

Figure 5: Relationship between reference pressure and average indicated pressure during increasing pressure.

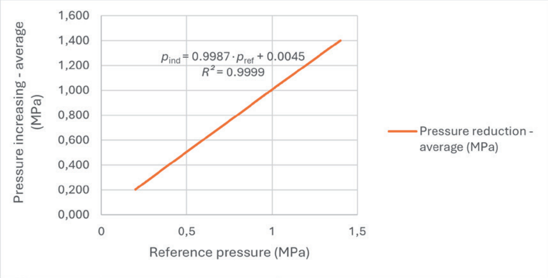

Figure 6: Relationship between reference pressure and average indicated pressure during decreasing pressure.

The coefficient of determination R2 was calculated for both regressions. This coefficient represents how well the regression line approximates the measured data. Its value ranges from 0 to 1, where:

- *R^2=0.9999 indicates a perfect agreement between the trend line and the measured values,*
- *values close to 1 indicate excellent linearity with minimal deviation.*

For both increasing and decreasing pressure sequences, the obtained value was R^2=0.9999. This result confirms an almost perfect linear dependence between the reference pressure and the gauge indication, which is consistent with the expected behaviour of a Bourdon-tube pressure gauge under controlled laboratory conditions.

To further evaluate the performance of the tested pressure gauge, the maximum deviation from linearity was calculated for both the increasing and decreasing pressure sequences. The deviation from linearity expresses how much the actual measured values differ from an ideal linear response defined by the regression function. The maximum deviation from linearity $\Delta_{\mathrm{lin,max}}$ is defined as:

$$\Delta_{\mathrm{lin,max}} = \max\left|p_{\mathrm{ind}} - p_{\mathrm{lin}}\right| \tag{3}$$

where p_{lin} – value predicted by the regression (trend) line at the same reference pressure.

The calculated maximum deviations for each measurement direction are summarised below:

Table 3: Maximum deviations from linearity for each measurement direction.

Measurement direction	Maximum deviation from linearity (MPa)	Relative deviation (%)
Pressure increasing	0.0075	0.47
Pressure reduction	0.0080	0.50

The results show that the maximum deviation from the idealised linear characteristic remains below 0.01 MPa in both cases. The relative deviations of 0.47 % (increasing pressure) and 0.50 % (decreasing pressure) are consistent with the expected performance of Bourdon-tube pressure gauges of accuracy class 1.0. The slightly higher deviation during pressure reduction corresponds to the minor hysteresis behaviour observed earlier.

The hysteresis error quantifies the difference between the increasing and decreasing pressure characteristics at identical measurement points. It is calculated as the relative maximum difference between the two characteristics:

$$H = \frac{\max\left|p_{\mathrm{ind,inc}} - p_{\mathrm{ind,red}}\right|}{p_{\mathrm{FS}}} \tag{4}$$

where $p_{\mathrm{ind,inc}}$ – indication during increasing pressure, $p_{\mathrm{ind,red}}$ – indication during decreasing pressure, p_{FS} – full-scale pressure (1.6 MPa).

The calculated hysteresis value was H = 0.42%. This low hysteresis confirms the mechanical stability and good elastic behaviour of the Bourdon tube within the tested pressure range. It also explains the small differences observed between the systematic errors in the ascending and descending pressure cycles.

Overall, the linearity and hysteresis results demonstrate that the tested pressure gauge exhibits highly predictable, repeatable, and nearly linear performance, fully consistent with instruments of accuracy class 1.0.

The overall measurement uncertainty was evaluated based on both repeated observations and known technical specifications of the measuring instruments. The calculation follows the standard methodology defined in the Guide to the Expression of Uncertainty in Measurement (GUM), where the combined standard uncertainty consists of a type A component (statistical) and a type B component (instrument-related).

The type A standard uncertainty arises from the statistical variability of repeated measurements of the pressure gauge reading at each calibration point. Since the observed data exhibited a very small scatter, it was assumed that the results follow a normal distribution. The standard uncertainty of type A was evaluated according to

$$u_A = \frac{s}{\sqrt{n'}} \qquad (5)$$

where s – sample standard deviation of repeated measurements, n – number of repetitions (in this case n = 10).

The type B uncertainty includes two independent contributions: the uncertainty of the tested Bourdon pressure gauge (Prema) and the uncertainty of the reference digital pressure gauge (Additel 681).

The maximum permissible error (MPE) of the tested gauge was calculated from its accuracy class as

$$\mathrm{MPE}_{\mathrm{Prema}} = \frac{\mathrm{FS} \cdot \text{accuracy class}}{100} \qquad (6)$$

Assuming a rectangular probability distribution, the corresponding type B standard uncertainty is

$$u_{B,\mathrm{Prema}} = \frac{\mathrm{MPE}_{\mathrm{Prema}}}{k}, \quad (k = 3) \qquad (7)$$

The manufacturer specifies the MPE of the Additel 681 as 0.020% of full scale (FS = 2 MPa):

$$u_{B,\mathrm{Additel}} = \frac{\mathrm{MPE}_{\mathrm{Additel}}}{k}, \quad (k = 3) \qquad (8)$$

The combined type B uncertainty is obtained by the root-sum-of-squares:

$$u_B = \sqrt{u_{B,\mathrm{Prema}}^2 + u_{B,\mathrm{Additel}}^2} \qquad (9)$$

The combined standard uncertainty of the measurement is therefore

$$u_C = \sqrt{u_A^2 + u_B^2} \qquad (10)$$

With a coverage factor k=3 (corresponding approximately to a 99.7% confidence level for normally distributed data), the expanded uncertainty becomes

$$U = k \cdot u_C \qquad (11)$$

Since the variation of individual components across pressure points was negligible, average values of u_A, u_B, and u_C were used to form the uncertainty budget. Table 4 presents the contribution of each component to the total variance of the measurement.

Table 4: Uncertainty budget and relative contributions.

Component	Standard uncertainty (MPa)	Relative contribution (%)
$u_{\mathrm{B,Prema}}$ (tested gauge)	0.0053	99.08
$u_{\mathrm{B,Additel}}$ (reference gauge)	0.0001	0.04
u_{A} (statistical component)	0.0005	0.88
Combined standard uncertainty u_{C}	0.0053	-
Expanded uncertainty U	0.0160	-

The uncertainty budget clearly demonstrates that the dominant source of measurement uncertainty is the MPE of the tested Bourdon gauge, which accounts for approximately 99% of the total standard uncertainty. The contribution of the reference pressure gauge is negligible, while the statistical component contributes less than 1%. This confirms that the calibration quality is primarily

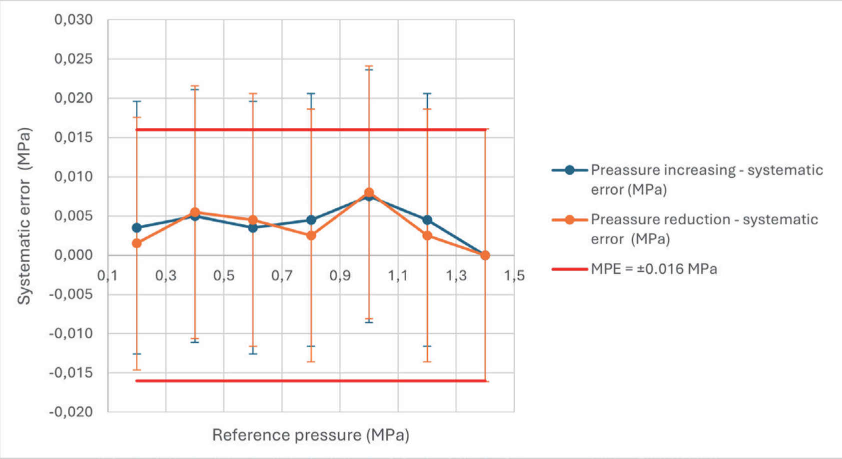

Figure 7: Systematic errors of the tested pressure gauge with expanded measurement uncertainties and MPE limits

limited by the design and accuracy class of the tested mechanical pressure gauge.

Figure 7 presents the systematic errors obtained at each calibration point for both increasing and decreasing pressure, together with the expanded uncertainty bars associated with the measurement. The red horizontal lines denote the maximum permissible error (MPE = ±0.016 MPa) of the tested pressure gauge according to its accuracy class.

The measured systematic errors themselves remain well within the limits defined by the MPE across the entire measurement range. This indicates that the inherent deviation of the tested Bourdon gauge does not exceed the accuracy requirements set by the manufacturer.

When the expanded uncertainties (coverage factor k=3) are included in the analysis, the upper and lower uncertainty bounds show a slight exceedance of the MPE at certain calibration points. This behaviour is expected, since the MPE is defined solely in relation to the observed indication error of the instrument, whereas it does not include any associated measurement uncertainty. The expanded uncertainty reflects the combined influence of all uncertainty components—statistical variability, the accuracy of the reference standard, and the intrinsic accuracy of the tested gauge—thus providing a more conservative interval.

In summary, despite the uncertainty bars marginally exceeding the MPE limits, the measured systematic errors comply with the specified accuracy class. The observed exceedance of the MPE by the expanded uncertainty therefore does not indicate non-conformity of the instrument but rather follows from the correct application of uncertainty propagation according to GUM principles.

4. Conclusions

This work presented the calibration of a mechanical Bourdon-tube pressure gauge with accuracy class 1.0 using a pneumatic pressure test pump Additel 914 and a high-precision digital reference gauge Additel 681. The experimental procedure included ten repeated measurement cycles during both increasing and decreasing pressure, covering the range from 0.2 MPa to 1.4 MPa. The results demonstrated that the tested gauge provides stable and repeatable indications across the entire measuring range.

The systematic error analysis confirmed that the deviations between the tested gauge and the reference instrument remain small, typically within 0.002–0.008 MPa. Only negligible differences were observed between the ascending and descending pressure sequences, indicating minimal hysteresis of the Bourdon-tube mechanism. The obtained linear regression models showed excellent linearity with coefficients of determination R^2=0.9999, which reflects the highly predictable behaviour of the instrument under controlled calibration conditions. The maximum deviation from linearity did not exceed 0.01 MPa, corresponding to relative deviations below 0.5%, and the calculated hysteresis error of 0.42% confirmed good mechanical stability of the pressure gauge.

An uncertainty analysis following the GUM methodology showed that the combined standard uncertainty of the calibration was u_C=0.00532MPa, and the expanded uncertainty for a coverage factor k=3 reached U= 0.0160 MPa. The dominant contribution (approximately 99%) originated from the maximum permissible error of the tested pressure gauge, while the uncertainty of the reference gauge and the statistical component contributed less than 1% combined. This confirms that the calibration accuracy is primarily limited by the intrinsic accuracy class of the tested instrument rather than by experimental variability or reference instrument performance.

Overall, the tested Bourdon pressure gauge meets the requirements of its accuracy class, with all measured systematic errors lying within the specified MPE limits. Although the expanded uncertainty intervals slightly exceeded the MPE at several points, this does not indicate non-conformity, as MPE limits apply only to the instrument's indication error and not to the full uncertainty range. The results validate that the gauge is suitable for practical industrial applications where accuracy class 1.0 is required, and the calibration procedure provides a reliable assessment of its metrological performance.

The presented study provides a clear, reproducible, and experimentally validated methodology for the calibration of mechanical pressure gauges using readily available laboratory equipment. One of the key advantages of the work is its practical orientation: the calibration procedure, the evaluation of systematic errors, linearity, hysteresis, and the detailed uncertainty analysis offer a complete framework that can be directly applied in industrial metrology, laboratory practice, and quality control environments. The article also demonstrates how to interpret calibration results in relation to MPE limits and expanded uncertainty, which is essential for determining the conformity of mechanical pressure gauges. Moreover, the study highlights the dominant sources of uncertainty and provides insights into the metrological behaviour of Bourdon-tube gauges, thereby supporting more informed decisions regarding instrument selection, maintenance, and verification intervals. The work thus contributes both scientifically and practically by offering a structured calibration approach, valuable reference data, and a realistic example of uncertainty budgeting in pressure metrology.

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