BULLETIN OF ENGINEERING SCIENCE, TECHNOLOGY AND INDUSTRY
(BESTI Journal) | ISSN (e): 3025-5821
Website : https://bestijournal.org/index.php/go/index | Volumes 4 No. 3 (2026)

UNCERTAINTY ANALYSIS OF PRESSURE GAUGE CALIBRATION: COMPARISON OF THE GUM AND MONTE CARLO METHODS

Aidil Arief Ananta[1]*, Irsyadi Yani[2], Barlin[3]
Sriwijaya University, Palembang
E-mail: aidilarief@gmail.com [1*], irsyadiyani@ft.unsri.ac.id [2], barlin@ft.unsri.ac.id [3]

Received: 20/05/2026 | **Revised:** 06/06/2026 | **Accepted:** 25/06/2026 | **Published:** 27/07/2026

Abstract

This paper presents a comparative uncertainty analysis of pressure gauge calibration using the Guide to the Expression of Uncertainty in Measurement (GUM) method and the Monte Carlo Simulation method. Pressure gauge calibration was conducted over a range of 0 to 25 bar to determine indication errors and their associated measurement uncertainties, which are vital for metrological traceability. The study evaluates several uncertainty contributors, including reference standard uncertainty, repeatability, resolution, zero deviation, and hysteresis. While the GUM approach utilizes a standard analytical framework based on linear approximations, the Monte Carlo method provides a probabilistic propagation of input distributions through 1,000,000 numerical iterations. The results demonstrate a high level of agreement between the two methods, with differences in expanded uncertainty remaining below 5% across the investigated range. Hysteresis and repeatability were identified as the dominant uncertainty components, particularly at higher pressure points. The findings confirm that the analytical GUM approach is reliable for this linear calibration model, while the Monte Carlo simulation serves as an effective complementary tool for validating complex or non-linear measurement problems.

Keywords: Pressure gauge calibration, GUM, Monte Carlo Simulation method, measurement uncertainty, hysteresis, repeatability.

INTRODUCTION

Pressure gauges are widely used in industrial processes, laboratory testing, and research applications. Their calibration should determine not only the indication error, but also the associated measurement uncertainty. This uncertainty is essential for traceability, compliance assessment, and the interpretation of calibration certificates The GUM framework remains the standard analytical method for uncertainty evaluation in metrology. It is transparent, efficient, and suitable for models that are close to linear and for input quantities that are approximately normally distributed. However, pressure gauge calibration often includes contributions from reference standard uncertainty, resolution, repeatability, hysteresis, temperature influence, drift, and interpolation between calibration points. When these effects are bounded, asymmetric, or strongly nonlinear, first-order uncertainty propagation may no longer fully represent the output distribution.

The Monte Carlo method addresses this limitation by numerically propagating the full input distributions through the measurement model. Instead of relying on linearization, it generates an empirical output distribution and allows coverage intervals to be taken directly from quantiles. For this reason, Monte Carlo is increasingly used as a complement to, or replacement for, the GUM approach in complex measurement problems. This paper compares both methods for pressure gauge calibration and identifies when the analytical approach is sufficient and when numerical simulation is more reliable. The introduction includes background on issues or problems, urgency and rationalization of service activities. The activity objectives and problem-solving plans are presented in this section. Relevant literature reviews and analysis of specific situations for service are included in this section. The citation and citation model used in the article is APA Style.

LITERATURE REVIEW

Pressure gauge calibration requires both an estimate of indication error and a defensible evaluation of measurement uncertainty. International calibration guidance commonly combines repeatability data with certificate-based and instrument-related contributions. Two widely used approaches for propagating these contributions are the analytical GUM framework and numerical Monte Carlo simulation

1. GUM Uncertainty Evaluation

Under the GUM framework, the combined standard uncertainty is evaluated as:

$$u_c(y) = \sqrt{\sum_{i=1}^{n} (c_i u(x_i))^2} \tag{1}$$

Where c_i are the sensitivity coefficient and $u(x_i)$ are standard uncertainty of the input quantities. The expanded uncertainty is then obtained as:

$$U = k \, . u_c(y) \tag{2}$$

With the coverage factor k is typically assumed to be 2 for an approximate 95% coverage probability when the output distribution is close to normal.

This approach is simple and effective, but it depends on the validity of the linear approximation and on the assumption that the combined output distribution is sufficiently symmetric[2].

2. Monte Carlo Uncertainty Evaluation

In the Monte Carlo method, each input quantity is represented by a probability distribution. For example, repeatability may be modelled by a normal distribution, resolution by a rectangular distribution, and a bounded correction term by a triangular or uniform distribution depending on the available information[3].

Many random samples are generated for all inputs, the measurement model is evaluated for each sample, and the resulting output values are used to construct the empirical distribution of the measurand. The coverage interval is then obtained from the relevant quantiles, typically the 2.5th and 97.5th percentiles for an approximate 95% interval[4].

This method is especially useful when the calibration model is nonlinear, when uncertainty sources are asymmetric, or when one input contributes a dominant bounded effect.

METHOD

1. Calibration Setup and Procedure

Pressure gauge calibration was performed over the range from 0 to 25 bar using a digital pressure test gauge as the reference standard. The reference standard had a range of 0 to 1500 psi (0 to 103.4 bar). Calibration points of 0, 5, 10, 15, 20, and 25 bar were evaluated in the increasing and decreasing pressure directions. Five repeated measurements were performed at the 15 bar point to assess repeatability and short-term stability

2. Measurement Model

For a pressure gauge under calibration, the indication error at a given reference pressure point can be written as:

$$E_i = P_{ind,i} - P_{ref,i} \tag{3}$$

where $P_{ind,i}$ is the gauge indication and $P_{ref,i}$ is the reference pressure provided by the standard. If a correction for zero offset or systematic bias is applied, the corrected error becomes:

$$E_{c,i} = E_i - b \tag{4}$$

where b is the estimated bias term.

The combined standard uncertainty of the corrected error depends on the uncertainty contributions of the reference standard, repeatability, resolution, hysteresis, temperature influence, and interpolation model [1].

3. Uncertainty Evaluation Procedure

The uncertainty evaluation followed the Guide to the Expression of Uncertainty in Measurement (GUM). Type A and Type B components were included. Repeatability was estimated from five repeated measurements at the 15 bar test point and was applied to the other calibration points. Reference-standard uncertainty was taken from the calibration certificate, while zero-deviation uncertainty was evaluated at 0 bar and propagated across the measurement range.

The uncertainty contributors included:

1. Repeatability (u_repeat);
2. Reference calibrator uncertainty (u_standard);
3. Instrument resolution (u_res);
4. Zero deviation (u_dev); and
5. Hysteresis (u_hys).

4. Monte Carlo Simulation Procedure

Monte Carlo simulation was performed using 1,000,000 iterations. Random values were generated according to the probability distribution assigned to each uncertainty source, and the measurement model was evaluated for every iteration. The 95% coverage interval was obtained from the 2.5th and 97.5th percentiles of the simulated output distribution.

The output-quantity model used in the simulation was:

$$Y = X_{ref} + e_{ref} + e_{rep} + e_{res} + e_{hys} \quad (5)$$

In this model, Y is the simulated output quantity, X_ref is the reference-pressure contribution, and e_ref, e_rep, e_res, and e_hys represent the reference-standard, repeatability, resolution, and hysteresis effects, respectively. Normal distributions were used for certificate-based contributions, while bounded resolution, zero-deviation, and hysteresis effects were represented by rectangular distributions in accordance with the available information.

5. Comparison Criteria

The two methods are compared using three criteria: the central estimate of the calibration error, the width of the expanded uncertainty interval, and the symmetry of the output distribution[5]. Agreement between the methods indicates that the calibration problem is well behaved and can be described adequately by first-order propagation. Divergence suggests that the output distribution is influenced by nonlinearity or non-normal input terms[6].

RESULTS AND DISCUSSION

Calibration Results

Table 1. Average calibration results obtained during the experiment.

Reference Pressure (bar) UP	Reference Pressure (bar) DOWN	Gauge Reading (bar)	Error (bar)
0	0.01	0	0
4.97	4.95	5	0.03
10.04	10.02	10	(-0.04)
15.09	15.08	15	(-0.09)
20	19.99	20	0
24.93	24.93	25	0.07

The results indicate that the pressure gauge exhibited relatively small deviations throughout the calibration range. The maximum observed error was (−0.09) bar at 15 bar gauge pressure. The calibration curve showed a nearly linear relationship between the reference pressure and the gauge reading, indicating acceptable instrument performance.

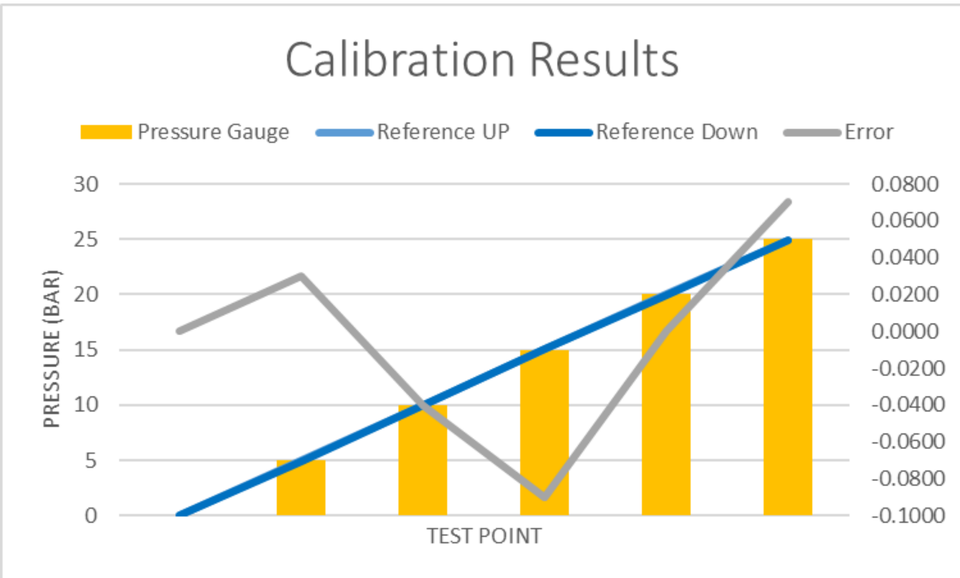

Fig. 1. Calibration results plot.

Repeatability Results

The repeatability test demonstrated stable readings with only minor fluctuations among repeated measurements, suggesting that the instrument maintained consistent performance during the calibration process.

Table 2. Repeatability test results.

Reference Pressure (bar)	Gauge Reading (bar)	Error (bar)
15.089	15	(-0.09)
15.069	15	(-0.07)
15.069	15	(-0.07)
15.072	15	(-0.072)
15.076	15	(-0.076)

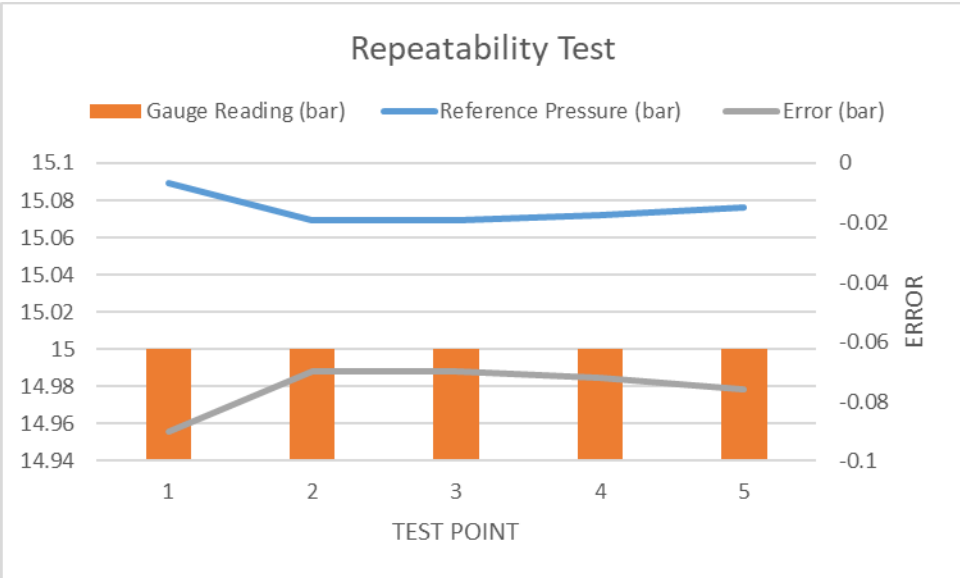

Fig. 2. Repeatability test results.

Uncertainty Budget Analysis

Table 3. Uncertainty budget at all calibration points.

Source of Uncertainty	Type	Distribution	U 0 bar	U 5 bar	U 10 bar	U 15 bar	U 20 bar	U 25 bar
Reference Calibrator	B	Normal	0.0000524	0.0047610	0.0047610	0.0047610	0.0047610	0.0047610
Repeatability	A	Rectangular	0.0000037	0.0000037	0.0000037	0.0000037	0.0000037	0.0000038
Resolution	B	Rectangular	0.0000333	0.0000333	0.0000333	0.0000333	0.0000333	0.0000333
Zero Deviation	B	Rectangular	0.0000333	0.0000333	0.0000333	0.0000333	0.0000333	0.0000333
Hysteresis	B	Rectangle	0.0001333	0.0001333	0.0001333	0.0001333	0.0001333	0.0001333
Expanded Uncertainty (k. Uc)			0.0320073	0.0318697	0.0318697	0.0317812	0.0317374	0.0316938

The maximum expanded uncertainty was approximately ±0.032 bar at the 0 bar test point. At this point, the reference calibrator was the largest individual uncertainty contributor.

Monte Carlo Simulation Results

The Monte Carlo simulation produced approximately symmetric, bell-shaped distributions centered close to the corrected calibration errors. The distribution at the final test point is shown in Fig. 3. The simulated results were consistent with the analytical uncertainty calculation and did not indicate significant skewness or nonlinear propagation effects.

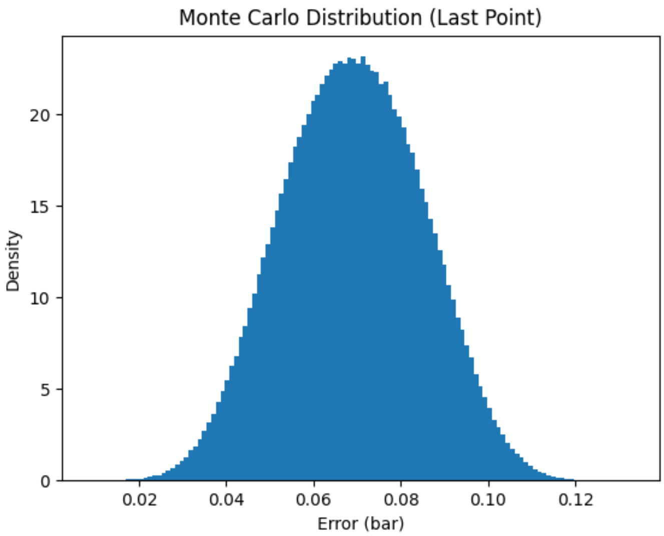

Fig. 3. Monte Carlo output distribution at the 25 bar test point.

The uncertainty results obtained using the GUM and Monte Carlo methods are summarized in Table 4.

Table 4. Comparison of expanded uncertainty obtained using GUM and Monte Carlo simulation.

Test Point (bar)	GUM Expanded Uncertainty (bar)	Monte Carlo Expanded Uncertainty (bar)	Difference (%)
0	0.0320073	0.03244	1.35
5	0.0318697	0.03236	1.53
10	0.0318253	0.03222	1.24
15	0.0317812	0.03223	1.41
20	0.0317374	0.03219	1.42
25	0.0316938	0.03213	1.37

The Monte Carlo results were very close to the analytical GUM calculations. Differences between the two methods ranged from approximately 1.24% to 1.53%, remaining well below 5%. This agreement validates the uncertainty model and indicates that first-order propagation is adequate for the investigated calibration system.

The repeatability component used in the Monte Carlo model was estimated from the repeated measurements at 15 bar and propagated to all calibration points. Therefore, the simulated uncertainty at 0 bar remained finite because repeatability, resolution, zero deviation, hysteresis, and reference-standard uncertainty were still present.

Hysteresis became increasingly important at the higher pressure points. This behavior may be associated with mechanical deformation, friction, and elastic recovery within the pressure-sensing mechanism.

Comparative Discussion

Monte Carlo simulation offers several advantages over conventional analytical propagation. It does not require strict linearity, can directly accommodate non-normal input distributions, and provides the full output probability distribution. In this study, however, the close agreement between the GUM and Monte Carlo results indicates that the calibration model was sufficiently linear and that the combined output distribution was approximately symmetric. Consequently, the GUM method is efficient and reliable for routine evaluation of this pressure gauge, while Monte Carlo simulation provides a useful independent validation tool. The results also show that improved control of hysteresis, repeatability, and reference-standard performance would provide the greatest opportunity to reduce the total calibration uncertainty.

CONCLUSION

Pressure gauge calibration over the range from 0 to 25 bar produced a maximum indication error of -0.09 bar at the 15 bar test point and a maximum expanded uncertainty of approximately ±0.032 bar. The expanded uncertainties obtained by Monte Carlo simulation differed from the GUM results by only about 1.24% to 1.53%, confirming strong agreement between the two approaches.

The close correspondence between the methods demonstrates that the analytical GUM approach is suitable for this essentially linear calibration model. Monte Carlo simulation remains valuable as a complementary validation method, particularly when future calibration models include nonlinear relationships, asymmetric distributions, or dominant bounded uncertainty sources.The conclusion explains what is expected in the Introduction section, as well as conclusions from the Results and Discussion section. Conclusions can also be added to the development plan for the implementation of the future service.

REFERENCES

[1] "Physikalisch-Technische Bundesanstalt Guideline DKD-R 6-1 Calibration of Pressure Gauges," 2014. [Online]. Available: www.dkd.eu
[2] "Guidelines on Calibration of Pressure measuring instrument_ Gauges, transmitters and transducers with electrical output".
[3] P. R. Guimaraes Couto, J. Carreteiro, and S. P. de Oliveir, "Monte Carlo Simulations Applied to Uncertainty in Measurement," in *Theory and Applications of Monte Carlo Simulations*, InTech, 2013. doi: 10.5772/53014.
[4] *Uncertainty of Force Measurements European Association of National Metrology Institutes*. [Online]. Available: www.euramet.org
[5] M. G. Cox and P. M. Harris, "Software Support for Metrology Best Practice Guide No. 6 Uncertainty Evaluation," 2010.
[6] V. Ramnath, "Comparison of the GUM and Monte Carlo measurement uncertainty techniques with application to effective area determination in pressure standards," 2010. doi: 10.1051/ijmqe/2010013.