

Application of non-dimensional uncertainty analysis to pressure sensors with electrical signal output

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ABSTRACT

This study focuses on the uncertainty analysis of pressure transducers, which are widely used in industrial applications. Pressure transducers convert mechanical pressure into electrical signals for measurement and monitoring across diverse sectors, like aerospace, automotive, and medical fields. The paper proposes a novel method for performing calibration uncertainty analysis through relativization, allowing the normalization of uncertainty contributions to various measurement parameters. By applying this approach, the study offers a standardized method to understand and quantify the impact of different sources of error on the overall measurement uncertainty. Furthermore, the techniques discussed in the study are applicable not only to pressure sensors but also to other measurement systems with multiple output units, contributing to the accuracy and reliability of measurement processes across various industries.

Section: RESEARCH PAPER

Keywords: pressure sensors; uncertainty analysis; relativization; calibration

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1. INTRODUCTION

Pressure sensors with electrical signal output, including electromechanical manometers and pressure transducers, play a vital role in various industries, including aerospace, automotive, manufacturing, and medical applications. These sensors convert mechanical pressure into an electrical signal that can be easily measured and processed, offering high precision and reliability. Electromechanical manometers typically operate on the basis of principles such as strain gauges, piezoelectric materials, or capacitive sensors [1], [2]. The electrical signal output generated by these devices varies depending on the type of pressure sensor and the technology employed. This output can be in the form of different signal types, such as voltage, current, resistance, frequency, or digital formats, each offering specific advantages depending on the application.

For example, the output signal may be a voltage, commonly in values like 5 V or 10 V, which directly corresponds to the level of pressure being measured. In some cases, the output may be a current signal, typically in the range of 4–20 mA, which is widely used in industrial applications due to its ability to transmit over long distances with minimal signal loss. Pressure transmitters can also output a relative change, such as 1 mV/V. In other cases, the output may be in the form of frequency modulation, where

the frequency of the signal corresponds to the pressure applied. Additionally, digital formats such as RS232 are used for transmitting data in a standardized way, enabling communication between sensors and digital systems or controllers. These varied output options allow flexible integration with different systems and ensure compatibility with a wide range of applications that require precise pressure measurements.

Pressure transducers typically use a sensing element that deforms in response to pressure, converting the mechanical displacement into an electrical signal, often through the use of a Wheatstone bridge circuit. The resulting signal is then processed to provide a pressure reading. These sensors have a wide range of applications, including fluid dynamics testing, industrial control systems, and environmental monitoring. One of the key advantages of pressure transducers with electrical output is their ability to offer high precision over a wide range of pressures, with small drift over time [3], [4].

A pressure transducer is a device that converts pressure into an analogue electrical signal. It typically works by altering resistance, capacitance, or voltage in response to changes in pressure. In contrast, a pressure transmitter also converts pressure into an electrical signal but generally incorporates additional circuitry to amplify, condition, and, in some cases,

Expectation: Linear Behaviour

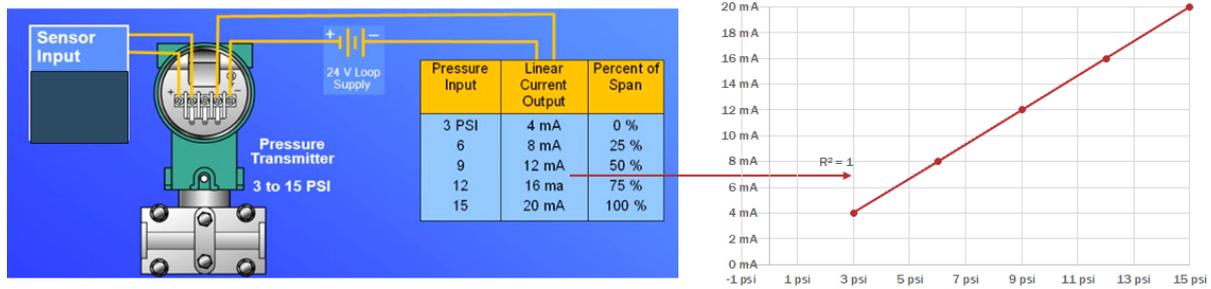


Figure 1. The expected behaviour of the pressure transducer.

digitally process the signal before transmitting it to a control system or display unit.

Pressure transducers usually provide a raw analogue output signal, such as voltage or current, which is directly proportional to the applied pressure. On the other hand, pressure transmitters typically offer a standardized output signal, such as 4–20 mA or 0–10 VDC, which is compatible with control systems, data loggers, or other instrumentation for easier integration. Pressure transducers are often integrated into larger systems where the raw analogue signal can be further processed as necessary. In contrast, pressure transmitters are typically standalone devices designed for direct use in control and monitoring systems with minimal need for additional signal conditioning.

It is expected that the electrical signal outputs of pressure transducers exhibit linear behaviour in response to incremental pressure. However, this is not always the case. The output may not always follow a perfectly linear pattern due to various factors, including the sensor's design, environmental conditions, manufacturing tolerances, and aging effects. Calibration is necessary to detect such discrepancies. The expected condition is shown in Figure 1.

Each measurement and calibration process will result in an uncertainty value. Making the best possible estimate of measurement uncertainty will allow the measurements to fall within a reliable range. Therefore, uncertainty analyses should be conducted, considering all the parameters that could affect the results as thoroughly as possible [5].

This study focuses on predicting measurement uncertainty in the calibration of pressure sensors with electrical signal output, through dimensionless transformation, based on the guidelines provided in the Guide to the Expression of Uncertainty in Measurement (GUM) [6], which outlines the principles and procedures for evaluating and expressing uncertainty in measurement results.

2. METHODS

In this section, the calibration method of pressure sensors with electrical signal output is explained. Additionally, the method for calculating measurement uncertainty is discussed.

Measurement uncertainty is a concept used to assess how reliable a measurement result is. Measurement uncertainty occurs from uncorrectable systematic errors and random errors. In this study, the uncertainty calculations of pressure gauges with electrical signal output were made using the dimensionless transformation method.

2.1. Calibration method

The calibration method of manometers is defined in the EURAMET cg-17 Guidelines on the Calibration of Electromechanical and Mechanical Manometers, and the calibration of pressure gauges with electrical output can also be performed according to the method defined in the document [7]. The calibration method is summarized in this section. The relevant details are provided below.

It is essential that the devices are shielded from direct sunlight, to prevent external factors from influencing the measurements. Both the reference and test devices should be positioned at the same level to ensure consistent readings. To achieve thermal stability before starting the calibration, the devices must be kept under controlled laboratory conditions. Calibration should only begin when both the environment and the devices have reached thermal equilibrium.

During the calibration process, the ambient conditions must remain stable. Temperature stability should be maintained within a ± 1 °C range throughout the calibration. It is also important to record the ambient conditions during the calibration.

An example of the calibration setup is provided in Figure 2. Here, the pressure gauge is connected to a pump and a reference pressure gauge to apply a gradual increase and decrease in pressure, and to read pressure values. To read the electrical signal corresponding to the applied pressure, the pressure gauge is connected to a calibrated multimeter. Additionally, the pressure gauge needs to be powered with an appropriate electrical voltage to function properly.

Before starting the calibration of transmitters and transducers, a visual inspection should be conducted to ensure that the test device is free from oil and dirt. According to the accuracy class, the number of measurement points is determined based on the



Figure 2. Illustration of an example calibration setup.

Calibration Procedure according to the EURAMET / cg-17 / v4.1

Calibration Procedure	Test device's accuracy class	Measuring points	Repeatability points	Load changing and waiting times	Waiting time at the upper limit of the device	Number of measurement series
Basic Calibration Procedure	$U \geq 0.2$ ($k = 2$)	(0, 10, 30, 50, 80, 100) %FS 6 points	At (0 % and 50 % FS) 3 times	> 30 s	2 s	1
Standard Calibration Procedure	$0.05 \leq U < 0.2$ ($k = 2$)	(0, 10, 20, 30, 40, 50, 60, 70, 80, 90, 100) %FS 11 points	At (0 %, 20 %, 50 % and 80 % FS) 3 times	> 30 s	2 s	1
Comprehensive Calibration Procedure	$U < 0.05$ ($k = 2$)	(0, 10, 20, 30, 40, 50, 60, 70, 80, 90, 100) %FS 11 points	3 measurements at all points	> 30 s	2 s	3

Figure 3. Calibration procedures according to EURAMET cg-17.

document EURAMET cg-17 Guidelines on the Calibration of Electromechanical and Mechanical Manometers, Version 4.1, 09/2022 [7]. For each measurement point, both increasing and decreasing pressure readings are taken. The waiting time for each measuring point, as well as the waiting time at the maximum scale, must be in accordance with the guidelines specified in EURAMET cg-17. The details of the calibration procedures defined in the EURAMET cg-17 document are shown in Figure 3.

Before proceeding with the calibration, the instrument should be brought to its upper pressure limit at least twice, and the pressure should be maintained for at least one minute, with a minimum of one minute waiting time between pre-loadings. A suitable calibration setup must be prepared by verifying the key characteristics of the device, including supply voltage, maximum loading pressure, and the type of pressure fluid used. Electrical power should be supplied to the test device a few hours before calibration, to ensure it is operational. Electrical connections should be made according to the manufacturer's connection diagrams, to ensure proper setup and accurate results.

During pre-loadings, it is important to check for any pressure drop in the calibration setup, and if there are no issues in the system, the measurement process can begin. The reference devices used for calibration should be traceable, and it is recommended to have an accredited calibration certificate for them, if possible.

After calibration, a report must be prepared, including the calculation of measurement uncertainty. An example of such a report,

prepared by the author, is shown in Figure 4. This report includes the applied pressure and the corresponding electrical signal readings for both increasing and decreasing pressure directions. Additionally, hysteresis and repeatability values are shared in the report. As supplementary information, the supply current and voltage values are also provided. Furthermore, the electrical signal values corresponding to the measured pressure points are presented in a graph, along with the single transmission coefficient. To assist the device user, a regression equation is provided and potential errors when using this equation are shared, along with the uncertainty associated with using the equation.

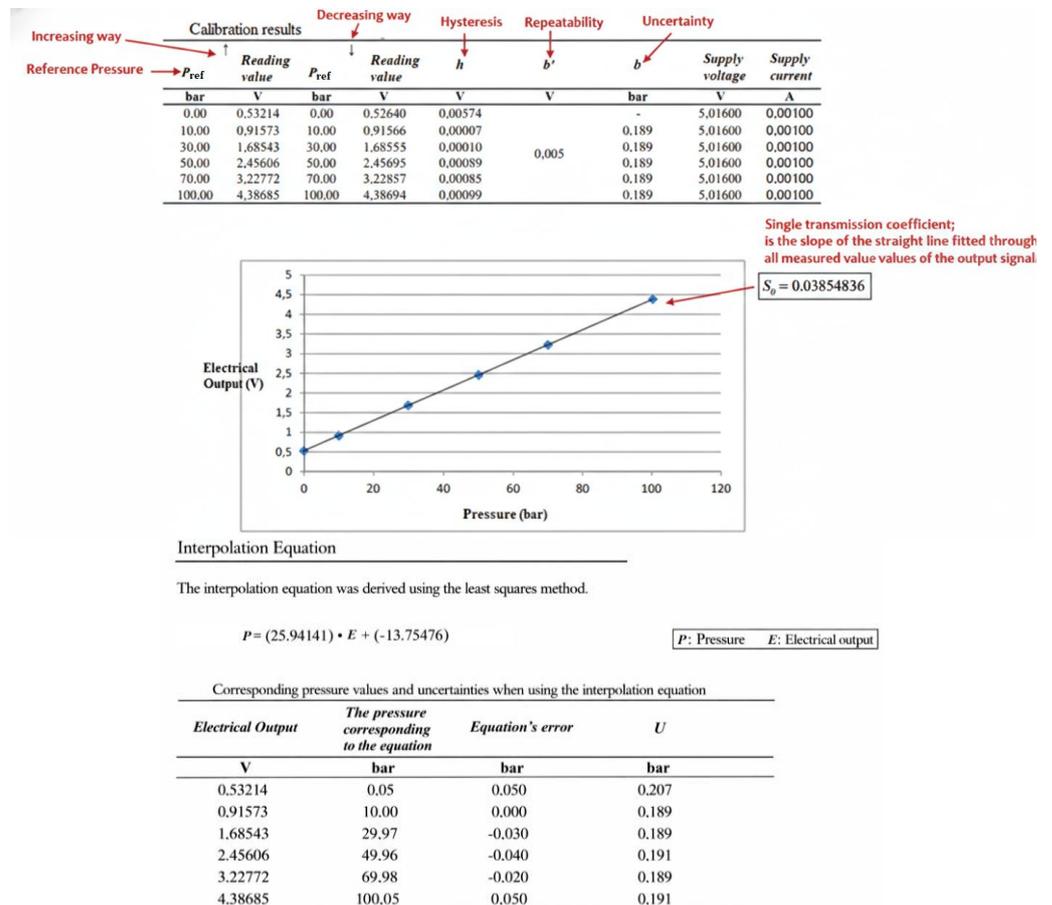


Figure 4. A sample calibration report.

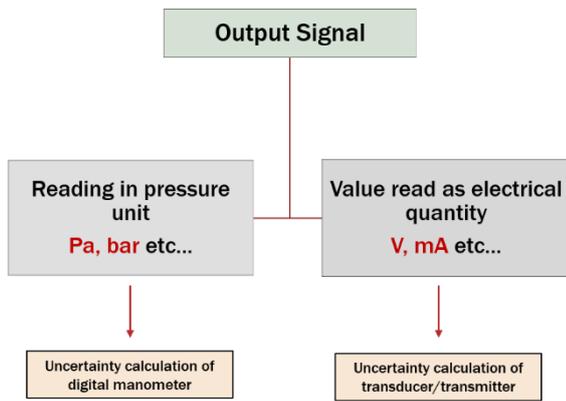


Figure 5. Uncertainty contributions.

2.2. Uncertainty contributions

In this section, the parameters affecting measurement uncertainty are defined, and the way of calculating these parameters is also discussed. Firstly, a functional representation can be made for the influencing parameters. Uncertainty contributions arise from potential sources of error. When calibrating a pressure gauge with an electrical signal output, both the electrical and pressure connections are made. Therefore, the uncertainty calculation will essentially be a combination of the uncertainty contributions arising from the measured pressure values and the measured electrical values. This situation can be explained as shown in Figure 5. Therefore, potential sources of error can be identified in the model function (1):

$$Y = f(U_{\text{ref}}, U_{\text{mult}}, \delta a_N, \delta z_N, \delta S_N, \delta H_N, \delta I_N). \quad (1)$$

Here, as the Y function, potential sources of error are provided. The uncertainty contribution from the calibration certificate of the reference pressure calibrator and the electrical multimeter, the resolution of the multimeter, zero error, repeatability value, hysteresis value, and possible errors due to the interpolation equation are expressed in the function. The relevant contributions can be defined as follows.

Uncertainty contribution from the calibration certificate of the reference device (U_{ref}): it is the uncertainty value declared by the laboratory that performed the calibration, as stated in the calibration certificate of the reference pressure calibrator.

Uncertainty contribution from the calibration certificate of the multimeter (U_{mult}): it is the uncertainty value stated in the calibration certificate of the device that performs the electrical signal reading, as declared by the laboratory that carried out the calibration.

Uncertainty contribution from the reading uncertainty of the multimeter's resolution (δa_N): when values are taken at measurement points on the multimeter, reading uncertainty occurs. In the measuring device, the smallest increment value represents the resolution.

Uncertainty contribution from zero error (δz_N): after the completion of measurements in the decreasing pressure direction on the transducer, a residual uncertainty component occurs due to the remaining zero value in the calibrator or multimeter.

Uncertainty contribution from repeatability measurements (δS_N): measurements are taken repeatedly under the same conditions on the transducer, and obtaining the same results from these measurements is expected. The largest difference between similar measurements contributes to uncertainty as the repeatability value.

Uncertainty contribution due to hysteresis (δH_N): measurements are taken from the same measurement points on the manometer in both increasing and decreasing directions. The difference between measurements at the same measurement point in the increasing and decreasing directions gives the hysteresis.

Uncertainty contribution due to interpolation error (δI_N): if the calibration certificate provides an interpolation equation for the customer to use, the largest difference between the results given by this equation and the measured results should be taken as the uncertainty contribution.

3. APPLICATION OF THE UNCERTAINTY ANALYSIS AND CALCULATIONS

This section includes the calculations, and an example demonstrates how the uncertainty analysis for the calibration of a pressure gauge with an electrical signal output is performed using the dimensional analysis method.

In the previous section, the contributions affecting the uncertainty calculation were provided, and each uncertainty contribution was made dimensionless by normalizing it to be relative. For example, a parameter in terms of pressure was divided by the applied pressure, while an electrical contribution was made relative by dividing it by the electrical signal output value at that point.

In practice, a pressure transducer with a capacity of 0–6 bar and an electrical signal output of 0–5 V have been used. The values read during the calibration process are shown in Figure 6. The basic calibration procedure outlined in the EURAMET cg-17 document has been applied. Additionally, the contributions affecting the uncertainty and the calculated values from the measurement result are shown in Figure 7.

The calculation of each uncertainty contribution is explained separately below. The relevant example calculations have been made for the 3-bar pressure point.

Uncertainty contribution from the calibration certificate of the reference device (U_{ref}): the uncertainty value in the calibration certificate of the pressure calibrator used as a reference has been combined with the drift and calculated as 0.2 bar ($k = 2$). Subsequently, this uncertainty value has been standardized and divided by the measured pressure value for de-unitization. The corresponding process is shown in Figure 8.

Uncertainty contribution from the calibration certificate of the multimeter (U_{mult}): the uncertainty value in the calibration certificate of the multimeter used for electrical measurements is 0.02 V ($k = 2$). After standardization, this value was divided by the measured 2.55 V value at the 3-bar point for relativization. The calculation step is shown in Figure 9.

Uncertainty contribution from the reading uncertainty of the multimeter's resolution (δa_N): the multimeter resolution is 0.01 V. This value is first standardized by dividing it by $2\sqrt{3}$, due to the symmetric situation of the rectangular distribution, and then relativization is performed by dividing it by the 2.55 V value, as given in the Figure 10.

Uncertainty contribution from zero error (δz_N): it was observed that there was no difference between the values read from the multimeter at the initial conditions and after completing the measurements. Therefore, the zero error was taken as 0.0 V. After standardizing the corresponding value by dividing it by the divisor of the symmetric rectangular distribution, it should be divided by the 2.55 V value for relativization. This is shown in Figure 11.

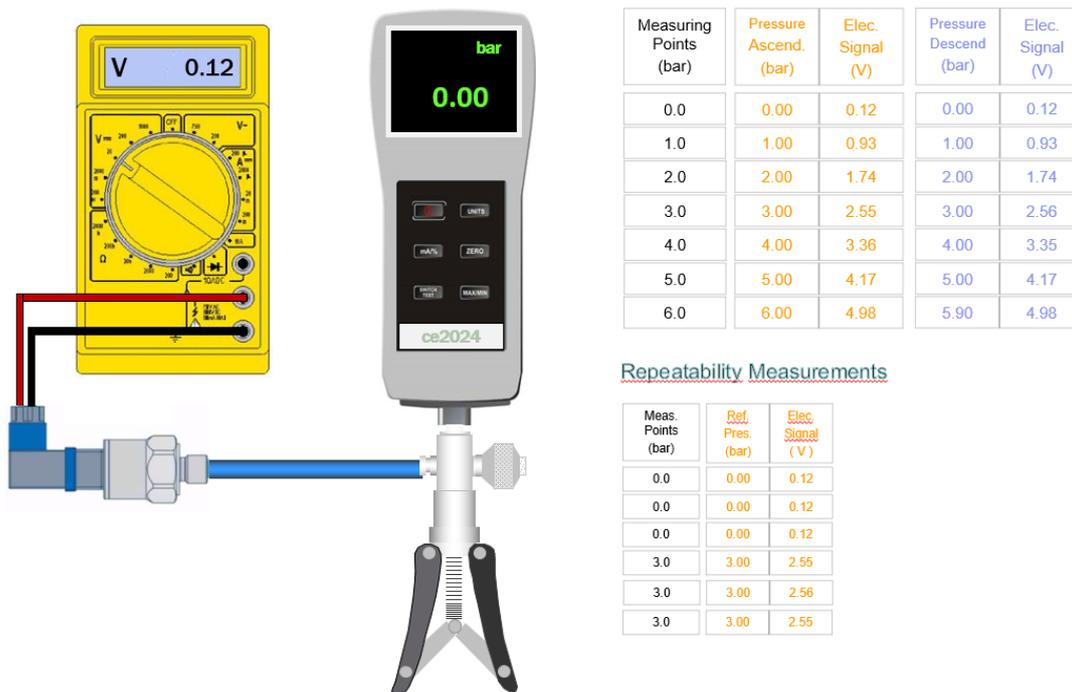


Figure 6. Calibration results in practice.

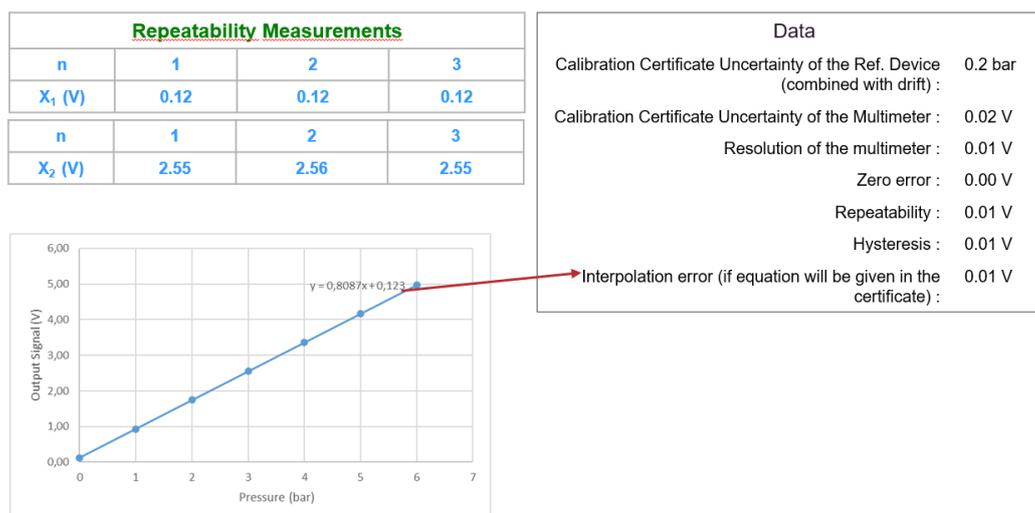


Figure 7. The data regarding the uncertainty effects resulting from the calibration.

Uncertainty contribution from repeatability measurements (δS_N): under the same conditions, electrical measurements were taken three times at both zero pressure and 3-bar pressure values. Each pressure point was evaluated individually, and the difference between the minimum and maximum electrical output signals gave the repeatability. The relevant value was divided by the divisor of the symmetric rectangular distribution and then divided by the read voltage value to perform the relativization. The calculations regarding the uncertainty contribution from the repeatability measurements are seen in Figure 12.

Uncertainty contribution due to hysteresis (δH_N): the difference between the electrical measurements taken in increasing and decreasing pressure directions at the relevant pressure point was found to be 0.01 V. After dividing this value by the divisor of the symmetric rectangular distribution, it is seen

Standard Uncertainty	$u_{\delta U_{kal}} = \frac{U_{kal}}{k} = \frac{0.2 \text{ bar}}{2} = 0.1 \text{ bar}$
Relativization (De-unitization)	$w_{kal,r} = \frac{0.2 \text{ bar}}{3 \text{ bar}} = 3.33 \cdot 10^{-2}$

Figure 8. Relativization of the effect of the reference pressure calibrator's calibration certificate.

Standard Uncertainty	$u_{\delta U_{Mult}} = \frac{U_{Mult}}{k} = \frac{0.02 \text{ V}}{2} = 0.01 \text{ V}$
Relativization (De-unitization)	$w_{Mult,r} = \frac{0.01 \text{ V}}{2.55 \text{ V}} = 3.9 \cdot 10^{-3}$

Figure 9. Relativization of the effect of the multimeter's calibration certificate.

Standard Uncertainty

$$u_{\delta a_N} = \frac{\delta a_N}{2\sqrt{3}} = \frac{0.01 \text{ V}}{2\sqrt{3}} = 0.003 \text{ V}$$

Relativization (De-unitization)

$$w_{\text{an.r}} = \frac{0.003 \text{ V}}{2.55 \text{ V}} = 1.2 \cdot 10^{-3}$$

Figure 10. Relativization of the effect of the multimeter's resolution.

Standard Uncertainty

$$u_{\delta z_N} = \frac{\delta z_N}{2\sqrt{3}} = \frac{0.00 \text{ V}}{2\sqrt{3}} = 0.00 \text{ V}$$

Relativization (De-unitization)

$$w_{\text{zn.r}} = \frac{0.00 \text{ V}}{2.55 \text{ V}} = 0.00$$

Figure 11. Relativization of the effect of zero error.

$\delta S_N = 2.55 \text{ V} - 2.56 \text{ V} = 0.01 \text{ V}$

Repeatability Measurements			
n	1	2	3
$X_i \text{ (V)}$	0.12	0.12	0.12

Repeatability Measurements			
n	1	2	3
$X_i \text{ (V)}$	2.55	2.56	2.55

Standard Uncertainty

$$u_{\delta S_N} = \frac{\delta S_N}{2\sqrt{3}} = \frac{0.01 \text{ V}}{2\sqrt{3}} = 0.003 \text{ V}$$

Relativization (De-unitization)

$$w_{\text{Nr}} = \frac{0.003 \text{ V}}{2.55 \text{ V}} = 1.2 \cdot 10^{-3}$$

Figure 12. Relativization of the effect of repeatability.

in Figure 13 that relativization was performed by dividing it by the measured electrical signal.

Uncertainty contribution due to interpolation error (δI_N): an interpolation equation (e.g., $a \cdot x + b$) corresponding to the pressure can be presented to the user for the electrical output. In this case, when the user uses this equation, there will be an error in the equation, and this error should be included in the uncertainty budget. In this application, the equation error has been taken as 0.1 bar. This value was divided by the divisor of the symmetric rectangular distribution and then divided by the measured pressure value of 3 bar to perform relativization, as shown in Figure 14.

After the relativized uncertainty contributions, the variances of each of them were taken and summed. Then the square roots were calculated to obtain the standard relative measurement

Standard Uncertainty

$$u_{\delta H_N} = \frac{\delta H_N}{2\sqrt{3}} = \frac{0.01 \text{ V}}{2\sqrt{3}} = 0.003 \text{ V}$$

Relativization (De-unitization)

$$w_{\text{H.r}} = \frac{0.003 \text{ V}}{2.55 \text{ V}} = 1.2 \cdot 10^{-3}$$

Figure 13. Relativization of the effect of hysteresis.

Standard Uncertainty

$$u_{\delta I_N} = \frac{\delta H_N}{2\sqrt{3}} = \frac{0.1 \text{ bar}}{2\sqrt{3}} = 0.03 \text{ bar}$$

Relativization (De-unitization)

$$w_{\text{In.r}} = \frac{0.03 \text{ bar}}{3 \text{ bar}} = 1 \cdot 10^{-2}$$

Figure 14. Relativization of the effect of interpolation error.

uncertainty ($k = 1$). Then, the relative measurement uncertainty was multiplied by the measured pressure value to obtain the measurement uncertainty in pressure unit ($k = 1$). For reporting purposes, the expanded measurement uncertainty value, providing a 95.44 % confidence interval, was obtained by multiplying it by $k = 2$, resulting in a value of 0.22 bar, as given in Figure 15.

If the single transmission coefficient is to be used by the user, the discrepancy between this single transmission coefficient and the transmission coefficient at each point should also be included in the uncertainty calculation (Figure 16).

4. DISCUSSION

In this study, an application was made regarding the calibration of pressure transducers, which are widely used in many industrial applications. These transducers provide an electrical output in response to pressure, allowing this electrical signal to be converted into pressure through automation systems. The uncertainty analysis was performed relative to the unit relativization after calibration, and the steps of the process were explained in detail. It is believed that this study will facilitate practical applications in the literature and serve as a reference point. Additionally, it is considered to be an insightful study for performing uncertainty analysis with relativization in different calibration applications.

Combined Measurement Uncertainty (Relative):

$$w_{\text{C.r}} = \sqrt{(w_{\text{kal.r}})^2 + (w_{\text{Mult.r}})^2 + (w_{\text{an.r}})^2 + (w_{\text{zn.r}})^2 + (w_{\text{Nr}})^2 + (w_{\text{H.r}})^2 + (w_{\text{In.r}})^2}$$

$$w_{\text{C.r}} = \sqrt{(3.33 \cdot 10^{-2})^2 + (3.9 \cdot 10^{-3})^2 + (1.2 \cdot 10^{-3})^2 + (0.00)^2 + (1.2 \cdot 10^{-3})^2 + (1.2 \cdot 10^{-3})^2 + (1 \cdot 10^{-2})^2} = 3.35 \cdot 10^{-2}$$

Combined Measurement Uncertainty:

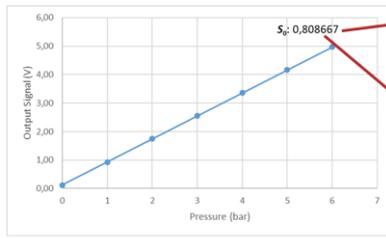
$$u_{\text{C}} = w_{\text{C.r}} \cdot p = 3.35 \cdot 10^{-2} \cdot 3 \text{ bar} = 0.11 \text{ bar}$$

Expanded Measurement Uncertainty:

$$U_{\text{G}} = k \cdot u_{\text{C}} = 0.11 \text{ bar} \cdot 2 = 0.22 \text{ bar}$$

Figure 15. Calculation of combined and expanded measurement uncertainty.

The error that will occur in the singular transformation coefficient of each point should be added to the uncertainty if the singular transformation coefficient is used.



Expanded Measurement Uncertainty (Relative):

$$W'_{G,r} = U_{G,r} + \Delta S = k \cdot u_c + \Delta S = (3.35 \cdot 10^{-2}) \cdot 2 + (4.1 \cdot 10^{-2}) = 10.8 \cdot 10^{-2}$$

Expanded Measurement Uncertainty:

$$U'_G = p \cdot W'_{G,r} = 3 \text{ bar} \cdot 10.8 \cdot 10^{-2} = 0.32 \text{ bar}$$

Transmission Coefficient for 3 bar		
Pressure	Output Signal	$S_{3\text{bar}}$
3 bar	2.55 V	$2.55/3 = 0.85$

$$\Delta S = |S_{3\text{bar}} - S_0| = 4.1 \cdot 10^{-2}$$

Figure 16. Measurement uncertainty when using singular transmission coefficient.

The aim of this study is to present a non-dimensional uncertainty analysis framework for pressure sensors with electrical signal output. It has been observed that such an approach has been scarcely explored in the field of pressure metrology, and the study aims to provide a method that can be easily implemented by users in practice. The dimensionless transformation approach allows different uncertainty sources to be evaluated within a unified framework. Moreover, the method offers a generalizable and transferable methodology that can be applied to various types of transducers. This study introduces a potentially standardizable technique for uncertainty evaluation.

5. CONCLUSIONS

The study introduces an approach to uncertainty analysis for the pressure transducer calibration through relativization, a technique that normalizes uncertainty contributions to the relevant measurement parameters. This method enables the conversion of each uncertainty component into a relative form, which makes it easier to compare different sources of uncertainty and assess their impact on the final measurement. By adopting this approach, the study provides a more comprehensive and standardized way of understanding the influence of each error source on the overall uncertainty budget, ensuring more reliable results.

The aim of this study is to establish a foundation for applications in pressure sensor calibration and provide a basis for efficient and standardized uncertainty analysis. Additionally, the techniques discussed in this work can be applied to different measurement systems that provide outputs with multiple measurement units.

AUTHORS' CONTRIBUTION

The sole author, Can Ekici, was responsible for the conceptualization, methodology development, data collection, analysis, manuscript writing, and final approval of the submitted version.

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