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Reducing the uncertainty of strain gauge amplifier calibration

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ABSTRACT
The article presents a method for calibration of strain gauge amplifiers with improved uncertainty in low voltage ratio range. The procedure is based on combining traditional calibration of the amplifier at one point and linearity check of the rest of the range. Traditional calibration is performed by a calibrated strain gauge bridge simulator at a reference value where measurement uncertainty is adequate, and the linearity check is performed by combinatorial calibration method with lower uncertainty, employing special resistance circuit. Uncertainty in the lower part of the amplifier range can be significantly improved, resulting in combined relative standard uncertainty below $1x10^{-5}$ for the range from 0,04 mV/V to 2,5 mV/V.

Section: RESEARCH PAPER

Keywords: calibration, strain gauge, simulator, amplifier, uncertainty

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1. INTRODUCTION

Strain gauge bridge transducers, which are used for measurement of mechanical quantities such as force, torque and pressure, need an instrument for excitation of the strain gauge bridge and for measurement and indication of the bridge output signal, which depends on the load applied to the transducer. Strain gauge bridge measuring amplifiers usually perform these tasks. They indicate the result of the measurement as the ratio of the bridge supply voltage and the bridge output voltage.

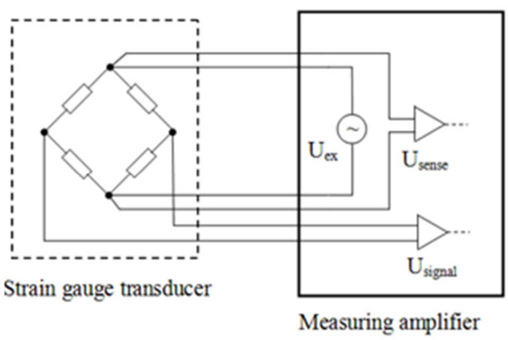

Figure 1. Strain gauge bridge transducer with 6-lead connection to the amplifier in a force measuring system.

Figure 1 shows a typical transducer–amplifier circuit in a 6-lead configuration.

As an important part of the measurement chain (or measuring system), measuring amplifiers should be verified regularly. This is usually performed by calibration with strain gauge bridge simulators, which provide defined voltage ratio values as reference values.

Such simulators, in turn, need to be calibrated themselves for each reference value they output. For high precision simulators (e.g. 225 Hz carrier frequency), typical expanded calibration uncertainty U of the 2 mV/V range is about 0,00001 mV/V at NMI level [1] and U=0,00002 mV/V at calibration laboratory level for further dissemination.

In the lower part of the range, such calibration uncertainties consecutively lead to large relative uncertainty of strain gauge amplifier measurement [2]. Figure 2 shows the relative standard uncertainty contribution of the simulator, if a calibration of the amplifier is performed with traditional calibrator units, such as HBM K3608 or HBM BN100A simulators. For U=0,00002 mV/V expanded calibration uncertainty, the relative standard uncertainty w at 2 mV/V is $5x10^{-6}$, rising to w=$5x10^{-5}$ at 0,2 mV/V, and to w=$2,5x10^{-4}$ at 0,04 mV/V (the typical 2 % low range limit of 2 mV/V nominal value of force transducers). Relative standard uncertainty of calibration at NMI level with U=0,00001 mV/V expanded uncertainty is also shown, where the relative standard uncertainty w reaches $1,25x10^{-4}$ at 0,04

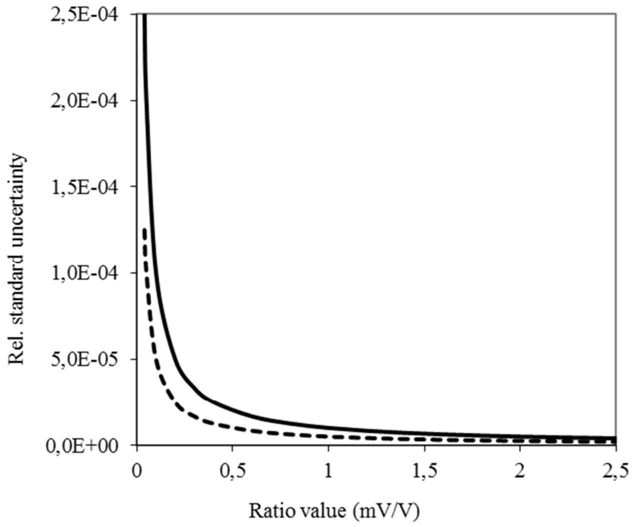

Figure 2. Relative standard uncertainty of typical calibrated high precision strain gauge simulator (solid line) and best available standard uncertainty at NMI level (dotted line).

mV/V ratio. Such uncertainties significantly exceed the available uncertainty of realization of mechanical quantities, where, for example, force standard machines offer uncertainties of W=1x10^{-5}.

Calibrating the amplifier together with the transducer as a measuring system is one solution to overcome this limitation, but it limits the transducer to be always used with the same amplifier. The transducer calibration can be void in the case of amplifier replacement, if the calibration data of amplifiers is not available.

If the transducer is used with other amplifier than the one employed originally during calibration, i.e. with a replacement amplifier, both amplifiers, original and replacement, should be calibrated, to assure comparability of results. Furthermore, deviations and calibration uncertainties of both amplifiers should be considered [7],[8]. If both amplifiers are not checked with the same simulator, where the simulator is used as a comparator rather than a traceable reference, uncertainty of the amplifier calibration should be evaluated and taken into account as necessary.

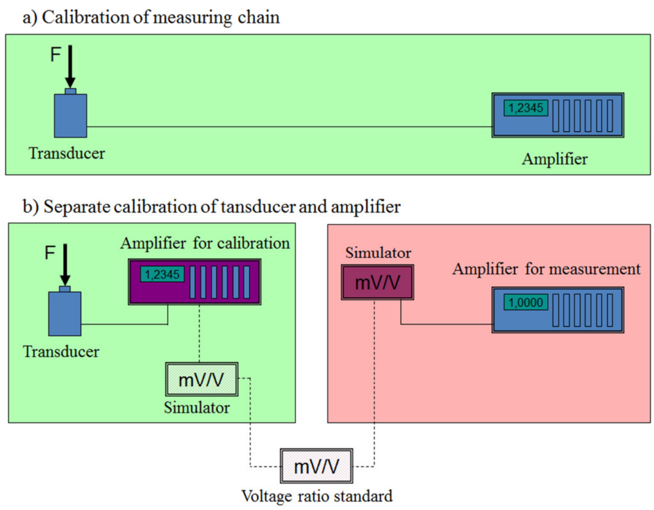

Figure 3. Comparison of calibration of (a) a measuring chain and (b) separate calibration of transducer and amplifier

According to the international standard ISO 376 [7], replacing the amplifier (called simplified an indicator in the standard) is allowed, if the following requirements are met:

- Both amplifiers should be calibrated and traceable to national standards.
- Both amplifiers should have the same working parameters (excitation voltage and frequency) and comparable resolution.
- Calibration uncertainties of original and replacement amplifiers should not significantly influence the total uncertainty of the force measuring chain. As a recommendation, the uncertainty of the replacement amplifier should not exceed 1/3 of the uncertainty of the entire system.

Whenever the amplifier is replaced, the contribution of the amplifier calibration should be compared against the calibration uncertainty of the measurement system, for the whole calibrated range, as the calibration uncertainty of the simulator can become the major uncertainty contribution and can increase the total measurement system uncertainty.

In section 2 we discuss the effect of replacement amplifier on the total measurement system uncertainty. Further, in section 3 we present a method and a circuit for checking the linearity of the amplifier without the need to first calibrate the circuit, thus allowing lower uncertainties. In section 4 we show the results for application of the method for linearity check on a high precision measuring amplifier. Finally, conclusion is given in section 5.

2. UNCERTAINTY CONTRIBUTION OF THE MEASURING AMPLIFIER

When a calibrated transducer-amplifier measuring chain is separated, the traceability of the system needs to be re-established via mV/V voltage ratio standard. A schematics of calibration of a measuring chain is shown in Figure 3(a) and necessary steps that are required for assuring exchangeability of measuring amplifiers via mV/V traceability is shown in Figure 3(b).

In the first case, the calibration is valid for the whole chain only, as the effects of transducer and amplifier are not individually known and therefore can not be separated. For such calibration, it is not possible to simply replace the amplifier, as the original amplifier characteristics (e.g. linearity, deviation) are not known. While the calibration results are typically ment for the transducer they are actually only valid for the force measuring system (transducer with original amplifier).

If the possibility of replacing the amplifier is required, then the calibration data for the transducer alone should be provided, and not for the whole system. Thus, the effect of the amplifier should be eliminated from the measuring chain. For this, the amplifier must first be calibrated, to assess the amplifier characteristics, then the influence of the amplifier should be considered, and either the calibrated values of the system should be corrected for any amplifier deviation or the necessary corrections included as an additional uncertainty component. In any case, the uncertainty of the calibration of the amplifier should also be included in the transducer calibration uncertainty.

Before the transducer can be used with a replacement amplifier, the replacement amplifier must first be calibrated, and any deviations should be taken into account (corrected or included as additional uncertainty component). Then, the calibration uncertainty of the replacement amplifier should be included in the uncertainty budget for the new measurement system.

To illustrate the scale of standard uncertainties of calibration of the amplifier with respect to the standard uncertainty of the measurement chain (transducer with amplifier), an example is given in Figure 4, based on calibration data for a 100 kN force transducer. The calibration uncertainty of the measuring chain is shown with a solid line, as a relative standard uncertainty. The force transducer in this example was calibrated in the range from 5 kN to 100 kN (5 % to 100 % of nominal range) in a force standard machine with 0,002 % expanded uncertainty. For comparison, the uncertainty of the calibration of the amplifier is shown with a dashed line, for nominal output of the transducer of 2 mV/V at nominal force value. The calibration uncertainty of the amplifier is specified as 0,00002 mV/V from 0,1 mV/V to 2 mV/V. It can be seen, that while the amplifier uncertainty is much lower than the measurement chain uncertainty for the upper range of the transducer, it significantly exceeds the measurement chain calibration uncertainty at lower force values. When replacing the amplifier, the uncertainty of both amplifiers should be taken into account, further increasing the effect of the amplifier calibration uncertainty.

Figure 5 shows the expanded uncertainty for the case where the 100 kN force transducer is calibrated together with the amplifier as a measuring chain (solid line), and the resulting expanded uncertainty when a replacement amplifier is used after calibration – dashed line. For the second case, the expanded uncertainty $w_{trans+amp}$ is calculated from contributions of the original calibration uncertainty of the transducer chain w_{trans} and additional calibration uncertainties of each amplifier (original amplifier – w_{amp_NMI} and replacement amplifier – w_{amp_LAB}), Equation 1. In this example, both amplifiers have the same calibration uncertainty contribution (best available).

$$W_{trans+amp} = 2 \cdot \sqrt{w_{trans}{}^2 + w_{amp\_NMI}{}^2 + w_{amp\_LAB}{}^2} \qquad (1)$$

As can be seen from the figure, the amplifier uncertainty exceeds 1/3 of transducer calibration uncertainty for values below 30 % of nominal range of the transducer. It results in a significant increase of the total uncertainty and should therefore not be neglected. This is also in agreement with the recommendation in ISO 376 regarding suitability of replacement amplifiers.

Table 1: Comparison of uncertainty contributions

Range	Output [mV/V]	U_amp [mV/V]	W_amp [%]	W_trans [%]
2 %	0,04	0,00002 (?)	0,050	/
5 %	0,1	0,00002	0,020	0,010
10 %	0,2	0,00002	0,010	0,009
20 %	0,4	0,00002	0,005	0,009
50 %	1,0	0,00002	0,002	0,008
100 %	2,0	0,00002	0,001	0,008

The contributions from amplifier calibration (absolute U_amp and relative W_amp) and from transducer chain calibration (W_trans) for the range from 2 % to 100 % of nominal transducer value are shown in Table 1. The output of the transducer ranges from 0,04 mV/V at 2 % to 2 mV/V at 100 % nominal range. The amplifier is not calibrated at 0,04 mV/V, but the uncertainty is estimated from the rest of the range.

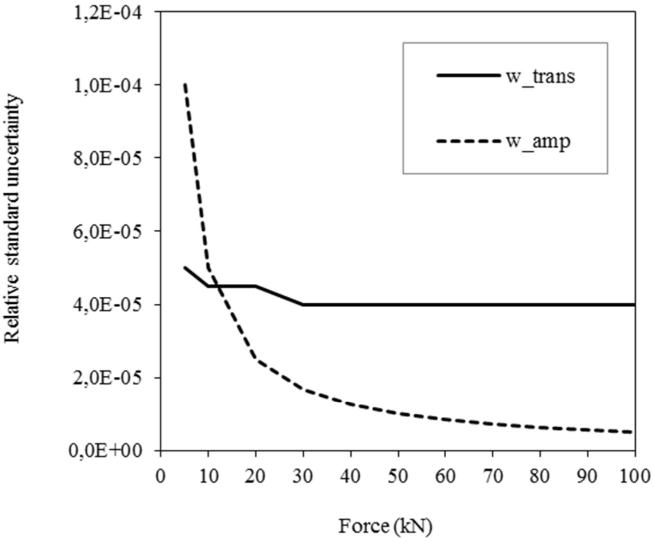

Figure 4. Comparison of relative standard uncertainty of calibration of a 100 kN force transducer chain (w_trans) and relative uncertainty of amplifier calibration (w_amp).

To reduce the effect of the amplifier calibration uncertainty and to keep the low uncertainty of measuring system calibration also at the lower values of the range, an additional evaluation of the amplifier can be performed by checking the linearity of the amplifier with low uncertainty. By calibrating the amplifier with a calibrated simulator at one reference value - at higher ratio values, where relative uncertainty is adequate - and using an alternative linearity check method with low uncertainty to verify the rest of the range, the measurement uncertainty in the lower range of the measuring system can be improved.

3. MEASUREMENT EQUIPMENT AND PROCEDURE

3.1. Combinatorial calibration method

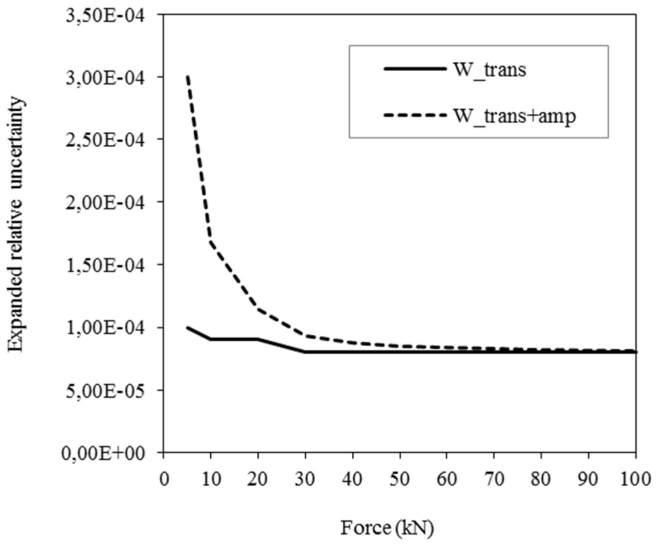

Figure 5. Comparison of expanded relative uncertainties of calibration of transducer chain (W_trans) and of calibration of transducer with replacement amplifier (W_trans+amp)

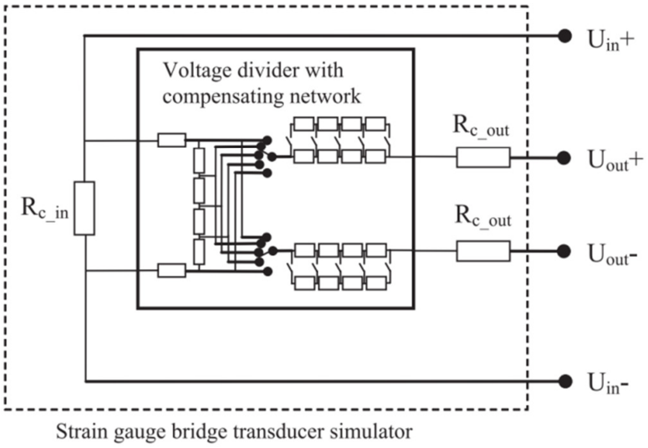

Figure 6. Strain gauge bridge transducer with 6-lead connection to the amplifier.

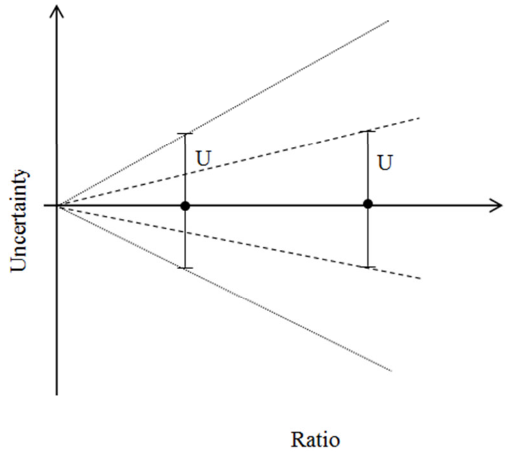

Figure 7. The uncertainty contribution of absolute calibration with respect to the selected calibration point.

To solve the problem of evaluation of measuring instruments, where the calibration of reference standards is too high, a calibration method that does not require traceably calibrated equipment can be applied [3]. The method, also called combinatorial method, has been in the last 20 years successfully applied in many different fields, e.g. thermometry bridge calibration [4].

The combinatorial calibration method is based on measuring a set of artefacts: each individual artefact separately and also all possible combinations of these artefacts. From the deviation of measured values of combinations of artefacts and calculated results from the same combinations, the non-linearity of the system can be estimated. Additionally, if one artefact is calibrated, a full calibration can also be performed.

3.2. Circuit for combinatorial method

To apply the combinatorial method to evaluation of measuring amplifiers, a suitable set of artefacts in necessary. A circuit fulfilling the requirements, which can also act as a strain gauge bridge simulator, is presented in [5]. A general schematics of the circuit employed for linearity check is shown in Figure 6. The circuit is based on a variable voltage divider comprised of base resistors, with additional resistor networks connected to the output leads of the divider to reduce the variation of the output resistance of the circuit. The output ratio is varied by tapping the output over a single base resistor or a combination of consecutive base resistors.

In the case of the circuit in Figure 6, the set of artefacts is defined by the four base resistors, which form a part of the voltage divider network. Output ratio of the circuit can be measured either for selection of each individual base resistor or for combinations of consecutive resistors.

Extending the circuit to eight base resistors allows measurements of 36 non-zero output combinations, from which the estimation of the linearity error can be calculated. The output ratios of the divider, as well as input and output resistance of the circuit, can be adapted to meet the requirements. The actual circuit built to check the linearity of the amplifier was designed for 350 Ohm input and output resistance and 2,5 mV/V nominal output ratio. With appropriately selected values for the eight base resistors, it can cover the range from about 0,04 mV/V to 2,5 mV/V.

3.3. Linearity check

Even without the calibration of the resistors, the circuit can be applied for the linearity check of measuring amplifiers. The circuit is connected to the amplifier in place of the transducer and the indication on the amplifier is recorded for each available output combination. When ratio values for all combinations have been measured, deviations of the measured sum of selected resistors and the calculated sum of selected resistors are determined. As the errors for base resistor are not known, they are estimated by a best fit, based on error distribution from all measurements. A fit is calculated for the resulting deviation values, and residuals of the fit serve as standard uncertainty estimation of the linearity measurement.

When the circuit is applied in combination with the combinatorial calibration method, the resulting uncertainty of the linearity check depends mainly on the quality of the measuring instrument. If it is applied to high precision amplifiers [6], it is possible to reach standard uncertainty of the linearity check of about 0,000002 mV/V.

3.4. Reference point calibration

The result of the linearity check alone is not enough to calibrate the amplifier. Additional traceable calibration must be made at least at one non-zero ratio value to establish the absolute error of the amplifier indication. For this purpose, traditional simulators can be employed, as, depending on the selected range, the simulator relative calibration uncertainty can be adequate for the required task.

Figure 7 shows the effect of the selection of the absolute calibration point on the scaling of its uncertainty contribution. The uncertainty contribution for values below the calibrated point is proportionally smaller and for values above the calibrated point proportionally larger. It is beneficial to choose the largest possible absolute calibration point, as it will provide the lowest uncertainty contribution in the lower part of the range. At the expense of increased uncertainty contribution, the calibration range can also be extended above the calibrated point.

4. RESULTS

The linearity check was performed on an HBM DMP41 high-precision 225 Hz carrier frequency amplifier. The selected parameters were 2,5 mV/V range, 5 V excitation voltage and 0,1 Hz Bessel filter. The expanded calibration uncertainty of the amplifier at 2 mV/V was U=0,00002 mV/V, or W=1x10^{-5}

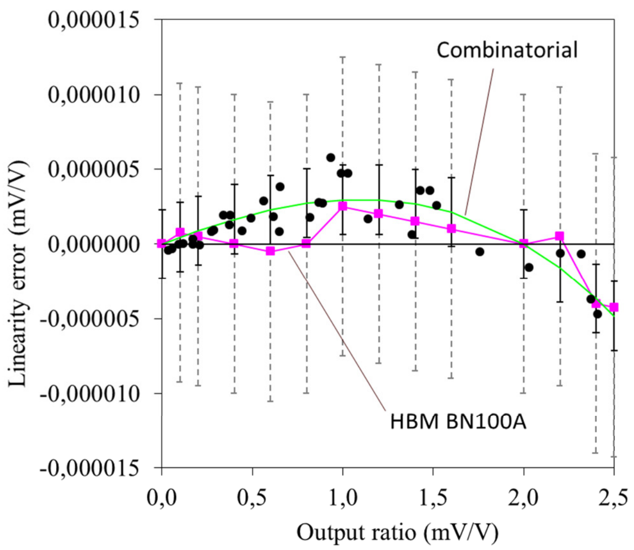

Figure 8. Linearity error for linearity check with combinatorial method vs. calibration with simulator - absolute error.

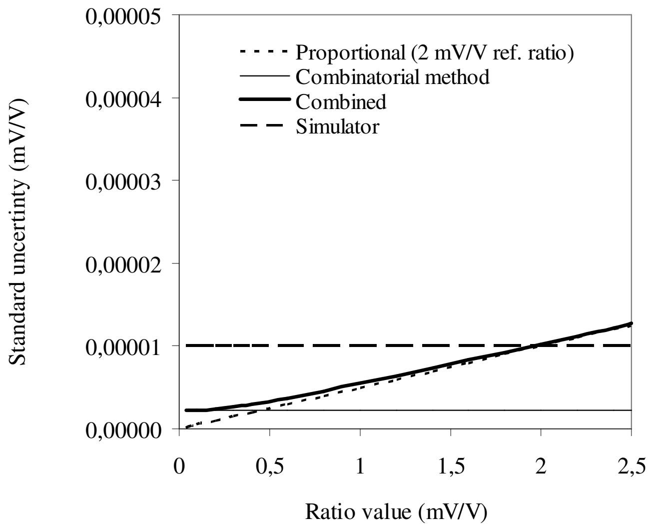

Figure 10. Combined standard uncertainty of absolute calibration at 2 mV/V (U=0,00002 mV/V) and linearity check for the whole range.

relative uncertainty. In combination with linearity check, the calibration of the amplifier in the whole range from 0,04 mV/V to 2,5 mV/V was performed.

Figure 8 shows the result of the linearity check with the combinatorial calibration method. The figure shows the resulting deviation of measurement of 36 possible resistor combinations, the fit of the linearity error and the estimated standard uncertainty. The calculated standard deviation of the residual errors is about 0,000002 mV/V, shown with solid uncertainty bars. Linearity check with a calibrated simulator HBM BN100A is also shown. The standard uncertainty of the linearity check of the amplifier, performed with the simulator, is shown with dotted uncertainty bars. For the comparison, the resulting curves are referenced at 0 mV/V and 2 mV/V.

Figure 9 shows the results from Figure 8 if they are expressed as relative deviations. The standard deviation of the residual errors in this case is $3{,}3\times10^{-6}$.

It can be seen, that while both measurements are in good agreement, the uncertainty of the linearity check with the combinatorial method produces lower uncertainty than linearity check with a calibrated simulator.

The results of the combinatorial calibration are sufficient to characterise the nonlinearity, but they do not provide enough information for the calibration of the amplifier, since the linear error is not known. Additional measurement at one ratio value is required to fully calibrate the instrument. If the absolute calibration at one point is made with U=0,00002 mV/V expanded uncertainty, it will define the minimum uncertainty at that point. Together with the linearity check uncertainty, the total calibration uncertainty of the instrument can be calculated.

Figure 10 shows the standard uncertainty contributions for the combination of absolute calibration of the amplifier at 2 mV/V and linearity check based on data from Figure 9, expressed in units of mV/V. The dashed line represents the calibration standard uncertainty of u=0,00001 mV/V. For linear

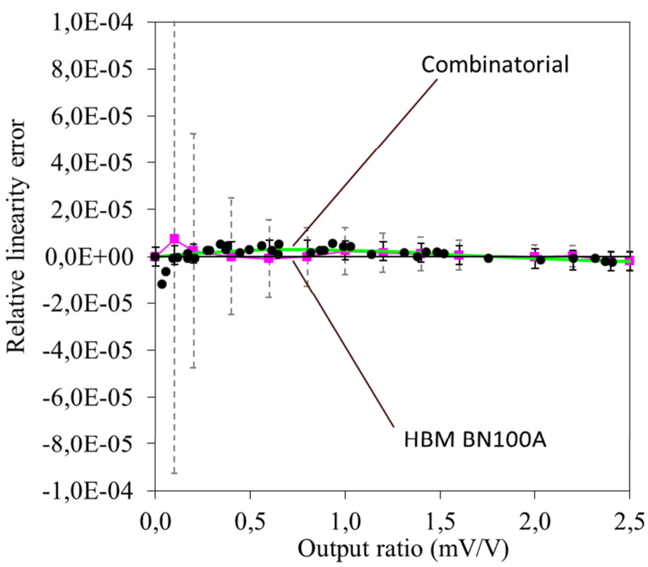

Figure 9. Linearity error for linearity check with combinatorial method vs. simulator calibration - expressed as relative error.

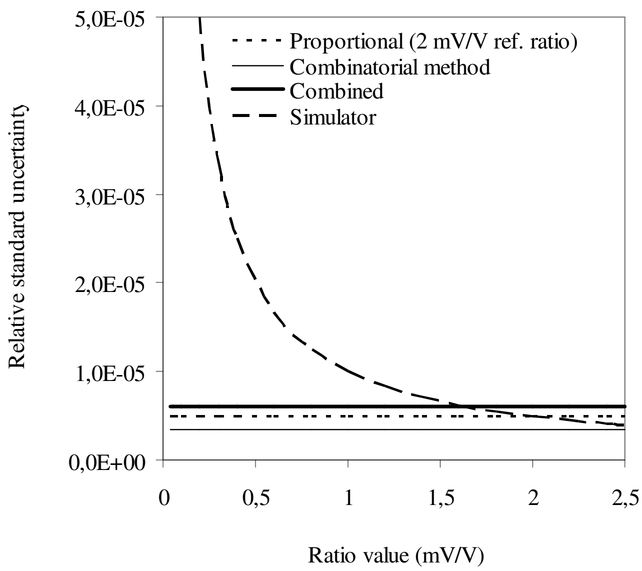

Figure 11. Combined standard uncertainty w of absolute calibration at 2 mV/V (U=0,00002 mV/V or W(2 mV/V)=1×10^{-5}) and uncertainty of the linearity check for the whole range.

instruments, this value can be scaled proportionally with the ratio value (dotted line) - the contribution due to simulator uncertainty. The second contribution is the standard uncertainty of the linearity check (thin solid line) performed with the resistor circuit and combinatorial method. The final combined standard uncertainty is shown as thick solid line. The combined uncertainty is calculated according to Equation 2, where u_c is the combined standard uncertainty, u_{sim_prop} the standard uncertainty contribution as proportional part of the absolute point calibration, and u_{lin_check} the standard uncertainty contribution of the linearity check employing combinatorial calibration method.

$$u_c = \sqrt{{u_{sim\_prop}}^2 + {u_{lin\_check}}^2} \quad (2)$$

It can be seen, that the dominant uncertainty contribution for most of the range is the calibration uncertainty arising from simulator calibration uncertainty. Compared to calibration employing only the simulator, the uncertainty has been reduced significantly in the lower range of ratio values, and slightly increased for ratio values above absolute calibration point.

In Figure 11, the same measurement example is shown, but standard uncertainty contributions are expressed as relative standard uncertainties based on Figure 7. We can see that the simulator calibration uncertainty increases significantly for lower ratio values (dashed line). The proportional part of the absolute calibration uncertainty at 2 mV/V, when expressed as relative uncertainty, is the same for the whole calibration range (dotted line). The contribution of the linearity check is shown as thin solid line. The combined relative standard uncertainty w is about 6x10^{-6} for the whole range of the instrument. If additional uncertainty component due to limited resolution is taken into account, it increases slightly the total uncertainty at lowest ratio values (below 0,1 mV/V), but the combined relative standard uncertainty w is still below 1x10^{-5}. Again, the reduced uncertainty compared to employing only the simulator is evident at low ratio values. Above 1,5 mV/V ratio, the uncertainty has been slightly increased.

In this paper, only calibration uncertainty of the amplifier calibration at one value and the uncertainty of the linearity check are considered. Other contributions, such as resolution of the instrument, drift of the simulator ratio value and other possible contributions are not explicitly taken into account.

5. CONCLUSIONS

The results of the evaluation show improvement in calibration uncertainty of measuring amplifiers in comparison to traditional strain gauge simulator calibration only. Combining the traditional simulator based calibration and combinatorial calibration based linearity check, improved calibration in the lower part of the range can be achieved. With the presented method, the relative standard uncertainty w at 0,04 mV/V can be reduced from typical values of 2,5x10^{-4} to values below 1x10^{-5}. The improved calibration uncertainty allows separate calibration of transducers and amplifiers and thus interchanging of transducer-amplifier combinations, while preserving acceptable calibration uncertainty levels for most scientific and industrial applications.

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