

## EXAMPLES OF STRAIN-GAUGE AMPLIFIER LINEARITY RESULTS USING COMBINATORIAL CALIBRATION METHOD

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**Abstract:** The paper presents results of linearity check of some widely used amplifiers for strain-gauge force, torque and other transducers. The combinatorial method is employed to achieve better uncertainty of the linearity check than using traditional voltage ratio calibrator units. Results for 225 Hz and 4800 Hz carrier frequency amplifiers and a DC amplifier are presented.

**Keywords:** amplifier, linearity, force, uncertainty

### 1. INTRODUCTION

Measuring amplifiers for strain-gauge based transducers are important part of the measuring chain. They also need to be evaluated and taken into consideration when defining the measurement uncertainty budget, especially if transducers are used with different amplifiers. Breaking the calibrated transducer-amplifier chain, by replacing the amplifier, requires measurement uncertainties of both amplifiers to be taken into consideration [1]. Traceable calibration of such amplifiers, in order to determine absolute accuracy or linearity, is only possible with relatively large measurement uncertainty, which is increasing for low mV/V values when expressed as relative uncertainty [2]. Typical expanded calibration uncertainty of high precision 225 Hz carrier frequency amplifiers is about 20 nV/V, while the expanded calibration uncertainty of DC and 4800 Hz carrier frequency amplifiers is easily an order of magnitude higher.

Even if traceable calibrated values are not required, but only linearity of the amplifier is of interest, the calibration uncertainty of reference values of the calibration equipment leads to similar uncertainty levels. Alternative procedure for linearity evaluation based on combinatorial method [3] was proposed in previous work [4], which enables improved standard uncertainty of the linearity check. The main advantage of the procedure is the possibility to omit the otherwise necessary calibration of the reference equipment while still producing linearity check results with attributed measurement uncertainty.

In the paper, the investigation of linearity of different strain-gauge amplifiers employing combinatorial method is presented.

### 2. EVALUATION METHOD

The employed combinatorial method is based on measuring a small set of base artefacts in a large number of possible combinations. After all possible combinations of

the base artefacts have been measured, the results of measured values of different combinations of artefacts and results calculated from the sums of base artefact value combinations are compared. The base artefact values do not have to be calibrated, as they can be estimated from the distribution of the error from all the measured combinations.

Traditional calibrator units are generally not suitable for application of combinatorial calibration method, as their output is usually referenced to a common point, not allowing independent combining of output ratios. To employ the combinatorial method for linearity evaluation of strain gauge amplifiers, a special circuit which simulates combinations of strain-gauge transducer output values is necessary [5], Fig. 1. The circuit is based on a resistive voltage divider with multiple output taps and it can output different base ratio values as well as combinations of these ratios.

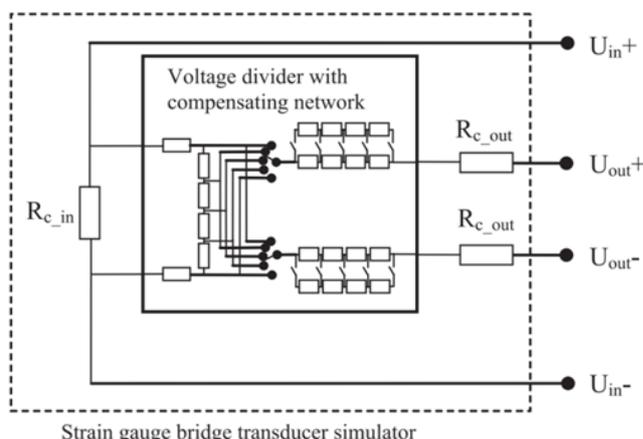


Fig. 1. Circuit for application of combinatorial method

The circuit comprises eight base resistors in the main divider chain (only four shown in Fig. 1) which determine eight base output ratios. By selecting different output tap pairs, different combinations of base ratios can be realized. The employed circuit can produce 36 combinations of ratio values from 8 base ratios. The resistance values in the main voltage divider chain were 20  $\Omega$ , 15  $\Omega$ , 11  $\Omega$ , 2.2  $\Omega$ , 1.5  $\Omega$ , 4.7  $\Omega$ , 6.8  $\Omega$  and 36  $\Omega$ , all having temperature coefficient of resistance 5 ppm/K, for good temperature stability during the measurement series. The nominal division ratio of the divider was selected to be about 1:400, with additional 40 k $\Omega$  resistance in the divider chain, to cover the output ratio range up to 2.5 mV/V. The input and output resistance of the circuit is about 350  $\Omega$ .

After connecting the circuit to the amplifier, the linearity of the amplifier is determined in two steps:

- in the first step, indicated values on the amplifier are recorded for all possible output ratio combinations of the circuit,

- in the second step, least-squares statistical analysis is performed on the measured results.

The first step is straightforward. After selecting a combination on the combinatorial circuit, the indicated value on the amplifier is recorded. This procedure is repeated for all 36 possible combinations.

In the second step, these recorded values are input into the least-squares fit calculation to estimate the base artefact values. This is achieved by minimizing the difference of measured and calculated values using least-squares analysis using Eq. 1 as described in [2], where  $s^2$  is the variance,  $N$  is the total number of combinations,  $n$  is the number of base artefacts,  $a_{i,meas}$  are indicated results for each combination, and  $a_{i,calc}$  are values calculated from fitted base values for each combination.

$$s^2 = \frac{1}{N - n} \sum_{i=1}^N (a_{i,meas} - a_{i,calc})^2 \quad (1)$$

After performing the least squares analysis, the standard deviation of the residual errors is taken as the standard uncertainty of the linearity check. The linearity of the amplifier is graphically represented as the deviation of the measured values from values calculated from the fitted base artefacts.

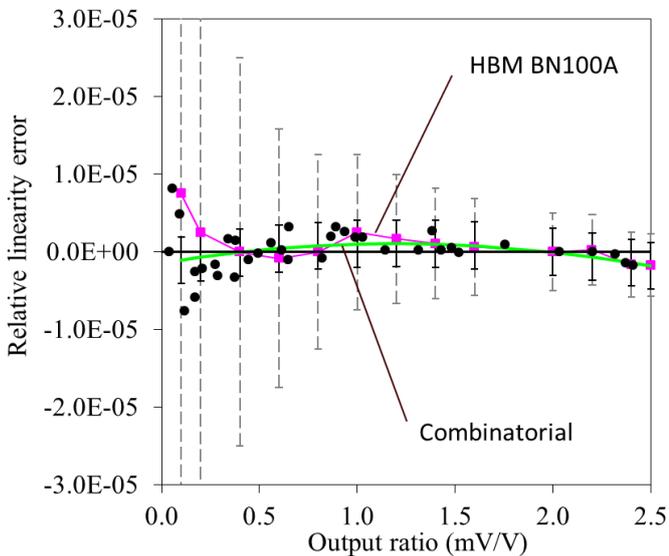


Fig. 2. Comparison of standard uncertainty: combinatorial method vs. traditional calibration with HBM BN100A calibrator

An example of improved standard uncertainty of the linearity check compared to traditional calibration is shown in Fig. 2, where the results are shown as relative linearity errors, with expressed relative standard uncertainty. The absolute calibration of the amplifier was performed with HBM BN100A calibrator unit with standard uncertainty of

calibration of 10 nV/V (dashed uncertainty bars), leading to increased relative uncertainty for lower ratio values. In comparison, the relative standard uncertainty of the evaluation using combinatorial method was about  $3 \times 10^{-6}$  (solid uncertainty bars).

### 3. EVALUATION PROCEDURE

The linearity evaluation was performed on widely used measuring amplifiers for strain-gauge based transducer employed for measurement of mechanical quantities such as force, torque and other transducers. The evaluated amplifiers were:

- HBM DMP41, 225 Hz carrier frequency
- HBM DMP40, 225 Hz carrier frequency
- HBM MX238B, 225 Hz carrier frequency
- HBM ML38B, 225 Hz carrier frequency
- HBM DK38, 225 Hz carrier frequency
- HBM ML55B, 4800 Hz carrier frequency
- GTM LT Digitizer, DC

All amplifiers were set to 2.5 mV/V range with 5 V excitation voltage. The evaluated range was from 0.04 mV/V to 2.4 mV/V.

The circuit was connected to each amplifier and left connected overnight to allow the system to thermally stabilize. Before the beginning of the evaluation, the measurement of zero and maximum value was checked to verify the stability of the system during the measurement period. The measurements included all 36 possible ratio combinations. The possible combinations of eight base resistors R1 to R8 are show in TABLE 1, with example of measured ratio values in mV/V. After each ratio was selected and the reading on the amplifier stabilized (depending on filter settings), the value was recorded. The switching of the output ratios was done manually via two rotary switches. After the measurement of all combinations, the zero and maximum values were rechecked.

When all measurement were made, the least-squares analysis was performed, and deviations of measured and calculated values for each measured point were determined. These deviations were plotted on separate graphs for each evaluated amplifier.

The resolution of the amplifiers was set to 1 nV/V, except for DK38, ML55B and LT-Digitizer, where it was 10 nV/V.

The filter settings on the amplifiers were set to 0.1 Hz Bessel type low pass filter, except for DK38 and LT-Digitizer, where filter values were selected to give stable indication within several seconds.

Typically, all the ratio combinations were measured within 30 minutes.

### 4. RESULTS

The results of linearity evaluation of each amplifier are presented as residual errors after the least squares analysis and are expressed as relative deviations. Depending on the amplifier type, the relative standard uncertainty of linearity evaluation ranges from about  $2 \times 10^{-6}$  to about  $7 \times 10^{-5}$  for the whole evaluated range of the amplifier as shown in Fig. 3 to

Fig 9. The results are shown for positive mV/V values, for each amplifier.

Fig. 3 shows the result of the evaluation of the linearity of an HBM DMP41 amplifier. The standard deviation of the residual errors is  $4.7 \times 10^{-6}$ .

Fig. 4 shows the result of the evaluation of the linearity of an HBM MX238B amplifier. The standard deviation of the residual errors is  $1.7 \times 10^{-6}$ .

Fig. 5 shows the result of the evaluation of the linearity of an HBM ML38B amplifier. The standard deviation of the residual errors is  $8.2 \times 10^{-6}$ .

Fig. 6 shows the result of the evaluation of the linearity of an HBM DMP40 amplifier. The standard deviation of the residual errors is  $1.8 \times 10^{-5}$ . In this case the evaluation of the amplifier was done with a version of the combinatorial calibration circuit with resistors with a higher temperature coefficient of resistance (50 ppm/K instead of 5 ppm/K).

Fig. 7 shows the result of the evaluation of the linearity of an HBM DK38 amplifier. The standard deviation of the residual errors is  $4.2 \times 10^{-5}$ .

Fig. 8 shows the result of the evaluation of the linearity of an HBM ML55B amplifier. The standard deviation of the residual errors is  $3.9 \times 10^{-5}$ .

TABLE 1: Possible combinations with example of indicated ratio values for each combination

N	Artefact combinations	Indication in mV/V
1	R1	0.498836
2	R1+R2	0.872986
3	R1+R2+R3	1.122589
4	R1+R2+R3+R4	1.178041
5	R1+R2+R3+R4+R5	1.213705
6	R1+R2+R3+R4+R5+R6	1.332512
7	R1+R2+R3+R4+R5+R6+R7	1.498868
8	R1+R2+R3+R4+R5+R6+R7+R8	2.399575
9	R2+R3+R4+R5+R6+R7+R8	1.900740
10	R2+R3+R4+R5+R6+R7	1.000032
11	R2+R3+R4+R5+R6	0.833674
12	R2+R3+R4+R5	0.714867
13	R2+R3+R4	0.679202
14	R2+R3	0.623749
15	R2	0.374146
16	R3	0.249601
17	R3+R4	0.305053
18	R3+R4+R5	0.340718
19	R3+R4+R5+R6	0.459525
20	R3+R4+R5+R6+R7	0.625881
21	R3+R4+R5+R6+R7+R8	1.526594
22	R4+R5+R6+R7+R8	1.276992
23	R4+R5+R6+R7	0.376280
24	R4+R5+R6	0.209923
25	R4+R5	0.091116
26	R4	0.055451
27	R5	0.035664
28	R5+R6	0.154471
29	R5+R6+R7	0.320827
30	R5+R6+R7+R8	1.221541
31	R6+R7+R8	1.185876
32	R6+R7	0.285163
33	R6	0.118806
34	R7	0.166355
35	R7+R8	1.067070
36	R8	0.900714

Fig. 9 shows the result of the evaluation of the linearity of a GTM LT-Digitizer amplifier. The standard deviation of the residual errors is  $6.7 \times 10^{-5}$ .

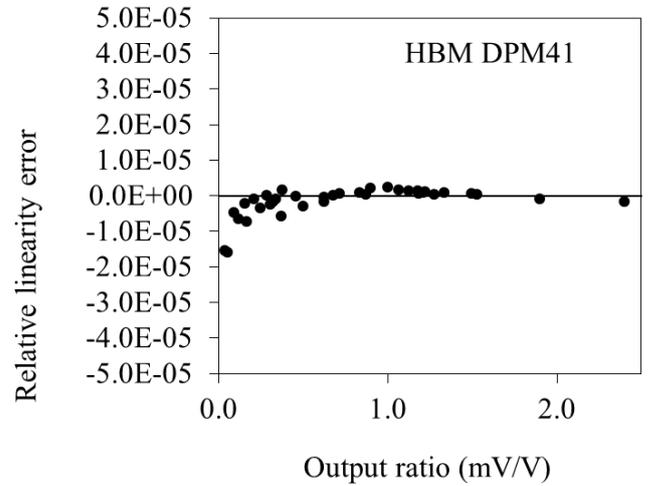


Fig. 3. Linearity evaluation of amplifier HBM DMP41

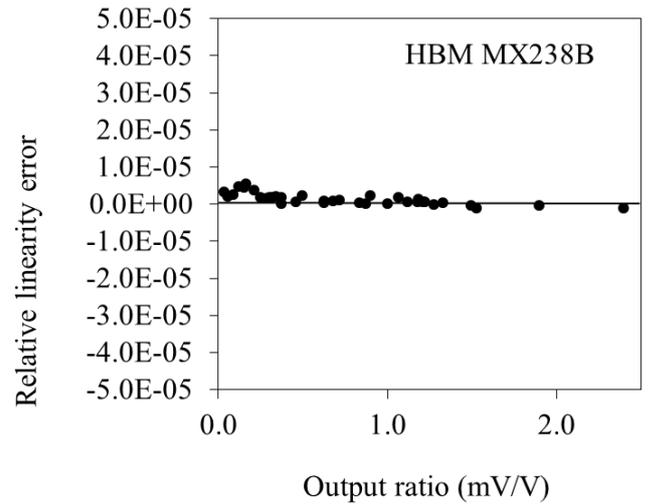


Fig. 4. Linearity evaluation of amplifier HBM MX238B

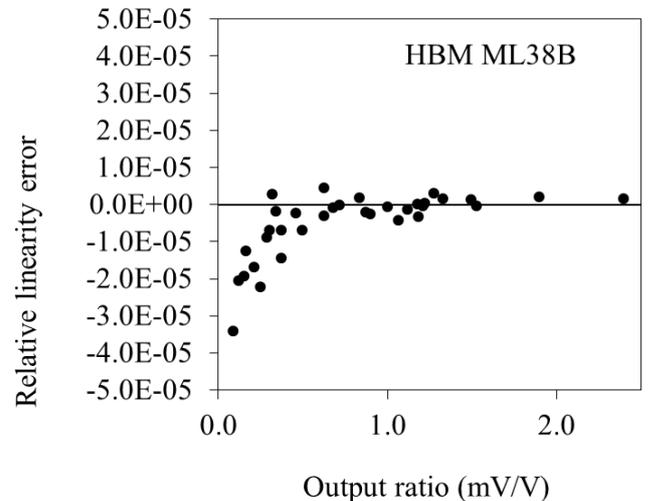


Fig. 5. Linearity evaluation of amplifier HBM ML38B

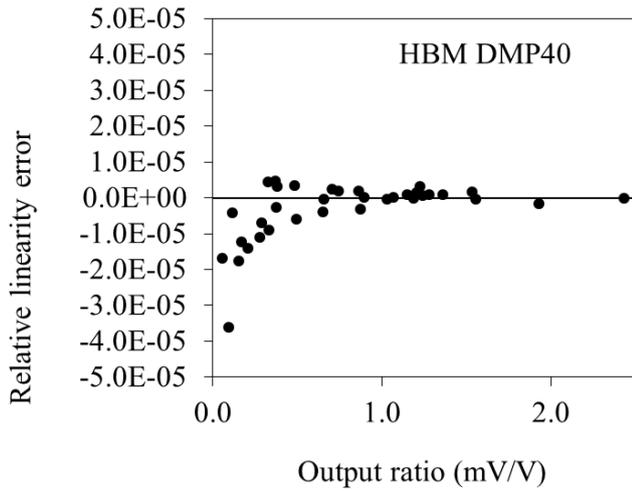


Fig. 6. Linearity evaluation of amplifier HBM DMP40

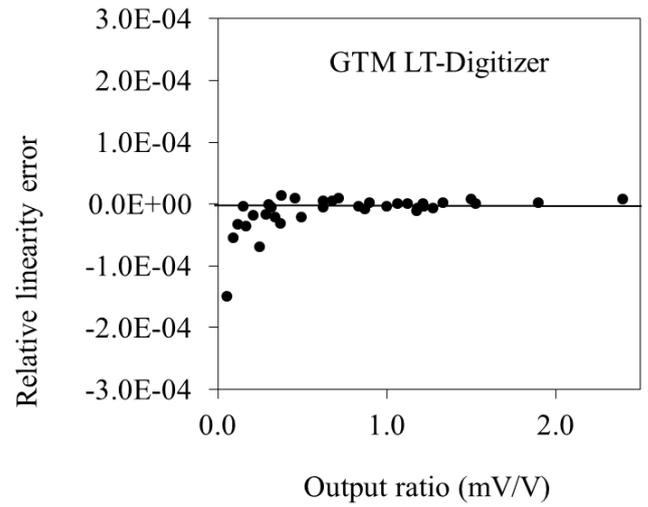


Fig. 9. Linearity evaluation of amplifier GTM LT-Digitizer

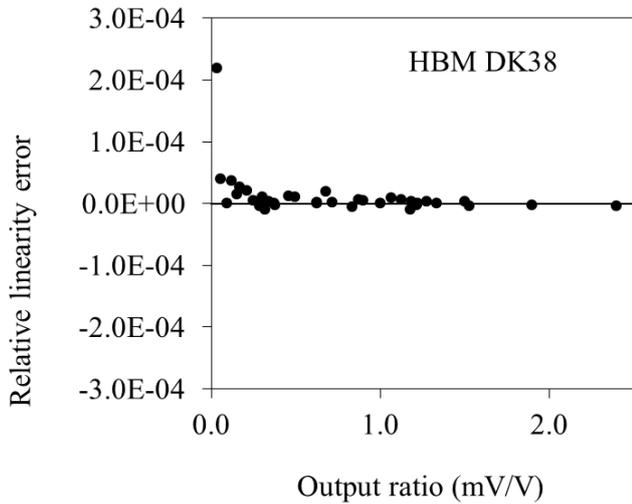


Fig. 7. Linearity evaluation of amplifier HBM DK38

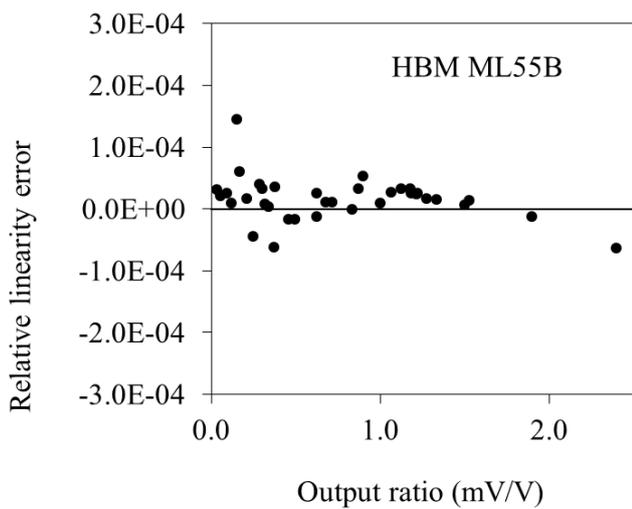


Fig. 8. Linearity evaluation of amplifier HBM ML55B

## 5. CONCLUSION

The presented results show the linearity evaluation of different measuring amplifiers with low standard uncertainty, not possible to achieve with traditional calibrators. The results of evaluation using combinatorial calibration method suggest very good linearity of measured amplifiers.

## 6. REFERENCES

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