XXI IMEKO World Congress "Measurement in Research and Industry"

30 August to 4 September, 2015, Prague, Czech Republic

UNDERESTIMATED IMPACT OF MEASURING CABLES ON HIGH-PRECISION CARRIER FREQUENCY AMPLIFIER RESULTS AND COMPENSATION METHODS THEREFOR

Marco M. Schäck

Hottinger Baldwin Messtechnik GmbH (HBM), Darmstadt, Germany, marco.schaeck@hbm.com

Abstract: The resolution when acquiring transducer results is physically limited. To ensure accurate measurements of resistive transducers in full bridge circuitry, in addition to the amplifier's precision, the use of appropriate measuring cables and their proper connection are very important.

Sources of errors with respect to the used measurement cables and their compensation to achieve the high accuracy class are shown. If these principles are not observed, there will be inescapably significant errors.

Keywords: precision instrument, strain gauge, physical limit, measuring cable, two-channel measurement method, auto- / background-calibration

1. INTRODUCTION

The resistance of a strain gauge changes under mechanical load. If several strain gauges are combined to a bridge circuit the ratio of the bridge output to the bridge excitation voltage is nearly proportional to the mechanical applied force. For the electrical measurement of mechanical quantities using strain gauges, it is the ratio of the voltages expressed in mV/V, which has great importance. The measured mechanical quantities are captured using transducers and are mapped into the unit mV/V.

The highest accuracies in the area of force and force comparison measurements are required at national and international levels from government institutions, which rely on DMP precision amplifiers from HBM. Figure 1 shows the new model of the DMP series from the front and back side, the DMP41.

In a previous publication, the measuring principle of the DMP41 is explained in detail [1]. There, the physical limits are shown. Beside the measuring principle and functional details like the carrier frequency method and the specially developed internal reference source, the patented new background-calibration is also described [2]. In a background-calibration (or background-adjustment) the drift of the amplifier is periodically compensated with an internal reference to keep the high class accuracy constant over temperature and lifetime. It was explained and shown that this new feature has no negative influence on the measurement. Measurements now can be taken reaching the limits of physical feasibility without any interruption. On this previous publication the following considerations are based on.

The developers of the DMP41 tried to eliminate all interference, or at least greatly reduce them, to achieve the maximum resolution at the physical limit. In addition to the effects on the device side there may be additional measurement errors on the user side. These include effects due to the measurement cables, which are the connecting elements between transducer and amplifier. The influence of the measuring cable is sometimes considerably underestimated, a few meter extension cord can degrade the accuracy class of a precision instrument by several orders of magnitude.

In this paper, the issue of measuring cables and their compensation is considered in more detail. Errors which are caused by the measuring cables and their compensatory opportunities are considered on the example of the precision measuring amplifier DMP41. However, these considerations can be applied to other amplifier. If these principles are not observed, there will be inescapably significant errors.

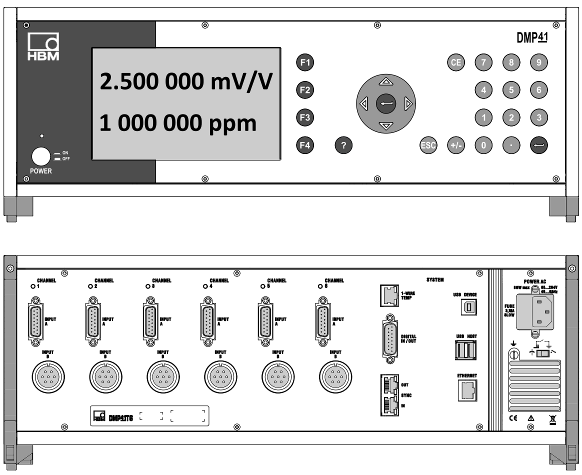

Figure 1: Front and back side of the DMP41 as table housing version

2. CAPACITIVE IMPACT OF THE MEASURING CABLE

The measurement technology asks for reliable and accurate results. The discussion about the advantages and disadvantages of DC and carrier frequency amplifiers for measurements of mechanical values has historical technical reasons [3]. Earlier tube amplifiers permitted for reasons of stability only the use of the carrier frequency technology.

With the introduction of semiconductor technology then the DC voltage technique reached importance. Since devices with very low carrier frequency and remarkable technical properties are available, the discussion has revived again. Internal and external interferences (e.g. temperature-dependent offset changes, noise of the semiconductors) are suppressed extremely effective by the carrier frequency amplifiers. The frequency range of the amplifier is designed so that only the carrier frequency is passing. All spurious frequencies located outside the carrier frequency and its own zero point drift can be suppressed.

The high-precision amplifiers operate typically at a carrier frequency of 225 Hz for quasi-static measurements of highest precision. Even at this low carrier frequency, the capacitive effects of the measuring cable affect significantly the measured values. The cores of a cable form capacitors between one another. Their capacitance depends on the length of the cores, the distance between them, their cross-section, their dielectric (insulation) and the temperature [4].

Figure 2 shows a simplified circuit of a measuring cable to connect a transducer with a given bridge impedance R_b to an amplifier. In the following the voltage drop and phase shift on the diagonals are calculated. For this analysis it is not relevant, if the sensor is connected in four- or six-wire technology. The equivalent circuit of the cable consists of the ohmic cable resistance R_c and the cable capacitance C_c [5]. The input impedance of the amplifier is neglected in this case.

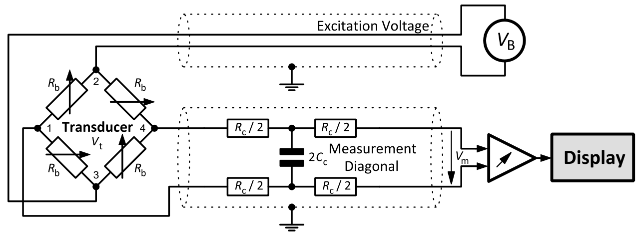

Figure 2: Simplified equivalent circuit of a measuring cable

Figure 3 shows the configuration of this measuring cable. It consists of three pairs of wires that are twisted and shielded. The inner pairwise shield is connected to the measuring ground of the amplifier (not to the housing or protective earth). A crosstalk between the line pairs is thereby prevented (e.g. crosstalk of the excitation voltage to the measuring diagonal). The differences in level of excitation and measurement voltage are gigantic, even small couplings can lead to large measurement errors.

A further shield around all pairs protects against external influences (concerning electromagnetic compatibility) [6]. The recommended sensor cable by HBM is sold by meter (Typ: Kab8/00-2/2/2, Ord.No.: 4-3301.0071). The cable sets for transducers in six-wire circuit also use exactly this cable. It has best available properties and may bridge distances up to several 100 m between transducer and amplifier [7]. The measurement cables are manufactured to narrow tolerance requirements.

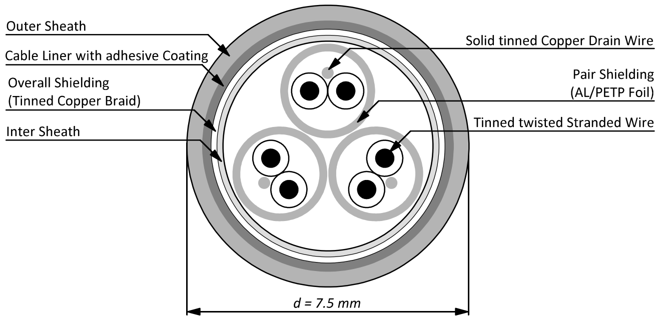

Figure 3: Structure of the recommended measurementcable

For this special measuring cable, a line resistance R_c of less than 140 Ω/km and a capacitance coating C_c of less than 130 pF/m is specified. Out of the measuring signal $V_t(\omega)$ from the transducer (1) the signal at the amplifier input $V_m(l)$ can be derived with the transfer function of the cable (2) for a given carrier frequency ω_c.

$$\overline{V_t(\omega)} = A\cos(\omega) \qquad \omega \xrightarrow{static} 0 \tag{1}$$

$$\overline{V_m(l)} \approx \frac{\frac{-i}{\omega_c C_c l}}{\frac{-i}{\omega_c C_c l} + \frac{R_b}{2} + \frac{R_c}{2} l}\,\overline{V_t(\omega)} \tag{2}$$

Under a quasistatic mechanical load A of the transducer the bridge provides as output a frequency equal to the supply voltage alternating frequency ω_C, the amplitude is proportional to the measured mechanical quantity. The transducers output voltage is amplified and the output voltage of the amplifier is fed to a demodulator. The demodulator has the function to rectify the alternating voltage signal with the correct sign [8]. The sign is of importance because of the direction of the measured mechanical quantity (e.g. tensile or compressive force). By capacitive effects occurs a phase shift between the measuring voltage and the control signal of the demodulator.

Figure 4 illustrates graphically the demodulation (rectangular demodulation for the DMP41) for the ideal case and in the case that there is a phase shift on the measuring diagonal. The output from the demodulator in both cases provides an alternating DC voltage. The following low-pass filter provides the shown mean DC voltage signal by integrating (filtering/averaging).

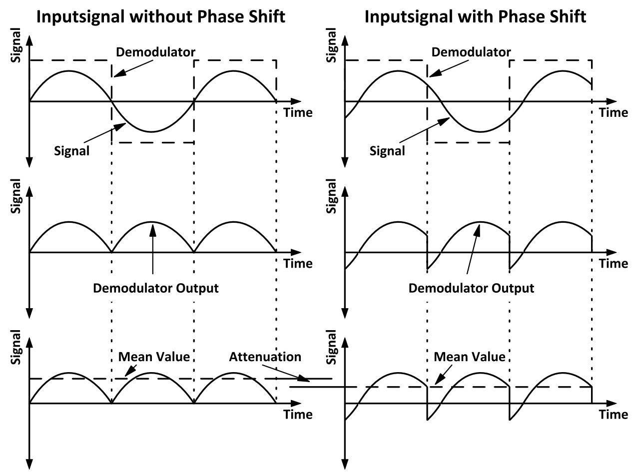

Figure 4: Demodulation of a signal with and without phase shift

If the phase of the measurement signal does not match with the reference phase, the demodulator provides negative portions of the alternating voltage at its output. Therefore the measurement signal is reduced. If the measurement signal is not in phase, there is a decrease of the mean value, at a phase shift of 180° there is even an inversion of the measured value.

The error due to the use of measuring cables consists of two errors, which leads to the attenuation of the amplitude. The capacitive load of the measuring cable causes a direct attenuation of the amplitude $\Delta V_{\mathrm{m,amp}}(l)$ at the amplifier input depending on the cable length l (3).

The second error is caused indirectly through this load as an attenuation of the amplitude $\Delta V_{\mathrm{m},\varphi}(l)$ by the phase shift of the measuring signal in relation to the reference phase of the amplifier (5) (reference phase is the phase of the demodulator V_{d} (4)). If the square demodulation is compared with the sinus demodulation, for both methods a phase shift leads to identical amplitude attenuation.

$$\Delta V_{\mathrm{m,amp}}(l) = 1 - \left|\frac{\overline{V_{\mathrm{m}}(l)}}{\overline{V_{\mathrm{t}}(l)}}\right| \tag{3}$$

$$V_{\mathrm{d}}(\omega) = \begin{cases} +1 & \text{for} \quad 0 \le \omega < \pi \\ -1 & \text{for} \quad \pi \le \omega < 2\pi \end{cases} \tag{4}$$

$$\Delta V_{\mathrm{m},\varphi}(l) = 1 - \frac{\int_0^{2\pi} sin(\omega + \varphi(\overline{V_{\mathrm{m}}(l)})\, V_{\mathrm{d}}(\omega)\, d\omega}{\int_0^{2\pi} sin(\omega)\, V_{\mathrm{d}}(\omega)\, d\omega} = cos\left(\varphi(\overline{V_{\mathrm{m}}(l)})\right) \tag{5}$$

As indicated in the equations before, the influence of the measurement cable also changes with the bridge impedance and the carrier frequency. The higher the carrier frequency and the higher the bridge resistance, the higher their influences on the measuring cable. Partly for this reason, the relatively low carrier frequency of 225 Hz was established therefore for precision measurement amplifiers.

For a transducer with a bridge impedance R_{b} of 350 Ω connected to the amplifier with a 225 Hz carrier frequency f_{c}, the voltage drop ΔV_{m} can be derived as a sum of both Errors ($\Delta V_{\mathrm{m,amp}}$ and $\Delta V_{\mathrm{m},\varphi}$) in dependence of the cable length l. Figure 6 shows this relationship in a double logarithmic scale. The curve is shown as a function of cable length for a typical application (R_{b} = 350 Ω and R_{b} = 4 kΩ). It should be mentioned that both errors ($\Delta V_{\mathrm{m,amp}}$ and $\Delta V_{\mathrm{m},\varphi}$) are exactly the same size.

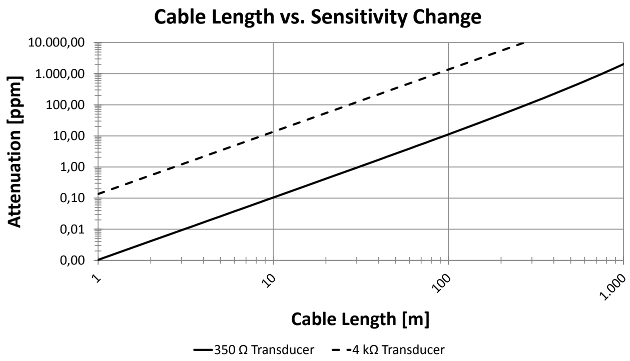

Figure 6: Influence the measured value depending on cable length

In this analysis, the input impedance of the amplifier (primarily capacitive) is not included. However, the input impedance has also still a significant effect on the measured value [9]. Depending on the used transducer impedance the class accuracy of high precision measuring amplifier will be left above a cable length of a few meters (for a 4 kΩ Transducer already at 6 m). In any case it is advisable to use low capacitance cable of high quality and to avoid unnecessarily long cables.

3. TWO-CHANNEL MEASUREMENT METHOD

It is possible to avoid the errors caused by measuring cables (resistive and capacitive effects). This technique is known as the two-channel measurement method (only for six-wire circuits). Amplifiers based on this dual-channel design can compensate the amplitude reduction and phase shift completely. To eliminate this type of error influences the two channel measuring method has been proven successful for decades.

The measuring channel which is detecting the measurement value and the measurement channel which detects the actual excitation must be constructed as identical as possible. Figure 5 shows the simplified circuit therefore. In the precision amplifier DMP41 these two inputs are built entirely symmetrical. The amplifier inputs are each represented simplified by a capacitor C_{in} and an ideal operational amplifier.

On the transducer side, the user has to ensure that the sense leads have the same source impedance as the measuring diagonals. The source impedance of each of the two measuring diagonals is half of the impedance of the full bridge R_{b}. These results in two matching resistors with the size of half bridge impedance $R_{\mathrm{b}}/2$

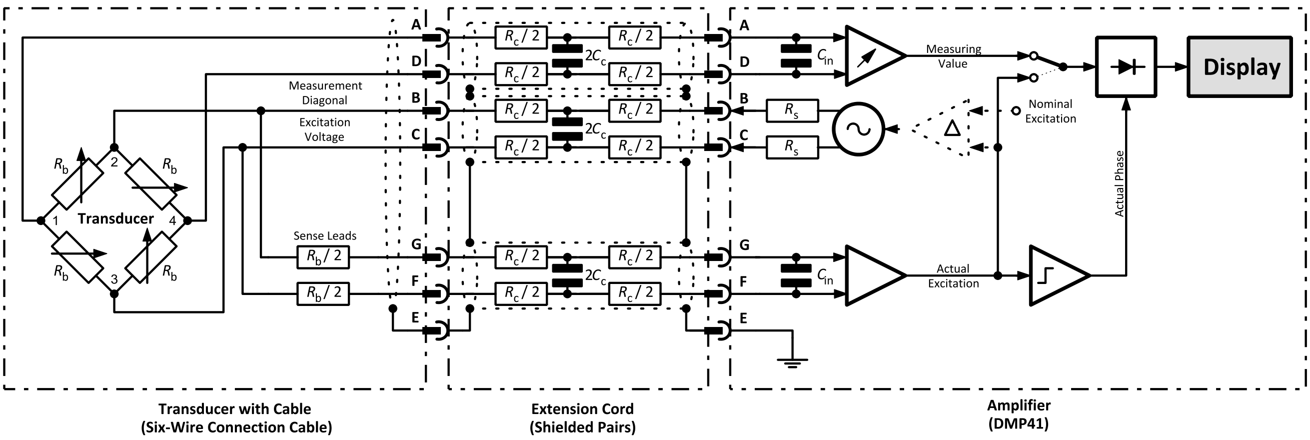

Figure 5: Two-channel measurement method with auto-calibration

for the sense leads on the transducer side. Thus, the sensed excitation voltage on the sense leads has the same amplitude attenuation and phase shift as the measurement signal.

Based on the symmetry, the ratio of diagonal voltage to excitation voltage at the amplifier is equal to the ratio at the transducer side, if the symmetry (cable parameters and source impedance) of the sense leads and the diagonal leads are equal. Because passive transducers with strain gauges represent the measured quantity by voltage ratios, it is important that these ratios are not distorted.

When the phase of the demodulator is also derived (directly or indirectly) from the sensed voltage, it gets the same phase shift as the measurement signal. The reference phase thus always has the optimal phase relationship to the measurement signal. If the measured signal and the sensed excitation voltage are measured sequentially from the same amplifier, the relation of these voltages will be in principle without errors.

This applies even if the voltage drops over the excitation leads by cable- R_c and outputresistance R_s are not compensated. However, this can be done in addition. With the use of a comparator (shown in dashed lines), the bridge supply voltage is readjusted so that both the amplitude reduction by a higher voltage and the phase shift by an earlier phase will be corrected. This is an additional part to prevent errors.

In a background calibration cycle of DMP41 the measuring signal will be set in relation to the returned excitation voltage. At the background calibration in addition the error of the amplifier is adjusted periodically. The new and patented background calibration is used in the DMP41 and was already explained in detail in a previous publication. With this new method, it is possible to periodically correct the error of the amplifier and to set the measurement signal in relation to the sensed excitation voltage without any measuring interruption.

For the first time in this accuracy class the data stream is not interrupted during an auto-calibration cycle. Compared to previous devices of the DMP series, where any auto-calibration cycle caused a data stream interruption. For this purpose, the predecessor of the DMP41 must periodically interrupt the measurement. The user has to consider this interruption and wait for new re-filter settling.

The basic principle of the device internal calibration and internal used reference is still the same since decades. Figure 7 shows the updated long-term stability of a HBM precision amplifier (DMP39) [10], which works exactly according to this principle (but with calibration interruptions). This characteristic can be transferred to the new precision measuring amplifier DMP41, with the advantage of uninterrupted streaming.

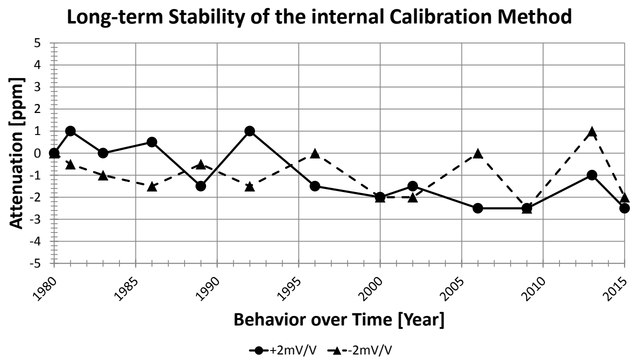

Figure 7: Long-term stability of the established calibration method measured with a DMP39 SN001 and BN100 SN010

4. $R_B/2$ MATCHING RESISTORS IN THE APPLICATION

There are transducers with four- or six-wires connecting cables. In the following the usage of the matching resistors $R_b/2$ for these cases is shown [11] [12]. These application guidelines are based on using a transducer with the measuring amplifier DMP41, but can also be transferred to other carrier frequency amplifier in six-wire circuitry.

For transducers with four-wire connection cables, the cable is a measurement part of the transducer itself. The calibrated and temperature compensated measurement signal is represented by the voltage ratio (measuring voltage / supply voltage) at the ends of the measuring cable. In this case, the measuring cable is included into the calibration. However, it still remains the non-negligible copper resistance change of 3.95 % / 10 K. Precision measurements should always be running in six-wire circuit and never in four-wire circuit [13]. A reduction or extension of these four-wire cables will change the calibration and temperature compensation of the transducers.

This is different for transducers in six-wire technology. Here, the interface for the calibrated transducer signal is located where the transducer supply voltage is sensed and passed through the sense leads to the amplifier. The connection cable of the transducers thus act as extension cord and is therefore actually not a measuring part of the transducer itself. Reducing or extending these six-wire cables is possible without changing the calibration or temperature compensation of the transducers, as it is the case for transducers with four-wire cables.

Figure 8 shows the correct connection of a sensor with four-wire connection cable to the amplifier with an additional optional extension cable. It is important that the feedback bridges or in this case matching resistors $R_b/2$ are located on the transducer side. This will also correct the influences of the used connectors.

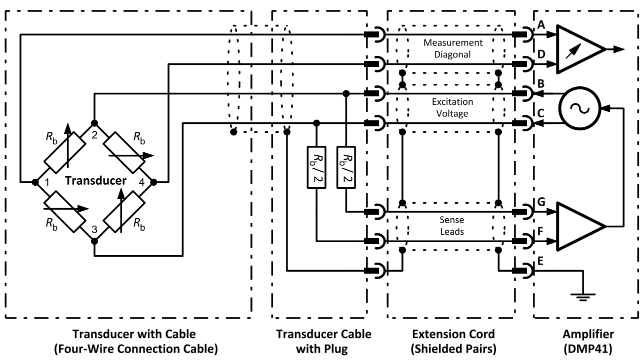

Figure 8: Transducer connection with matching resistors (four-wire)

Under proper connection six-wire transducers may nevertheless have a minor problem: Correctly, the two matching resistors have to be connected in the transducer directly at the sense voltage taps. There may be measuring amplifiers that have problems with the increased internal resistance (matching resistors) of the sense leads. Therefore, the matching resistors are not installed direct in the transducer. The problem is solved differently here, so the matching resistors can be installed later by the user.

Figure 9 shows the two matching resistors $R_b/2$ which are located at the connector side of the transducer. The user can independently install these matching resistors in the plug or remove them as well. Because the transducer cables in general are short, this results in no measurable errors. If no additional extension cable is used, the matching resistors can be omitted in both two cases. In the following, the amplitude sensitivity change without matching resistors is shown as a function of cable length. The user has to decide which sensitivity change is acceptable. Usage of these resistors without extension cable has no negative influence on the measurement at the DMP41.

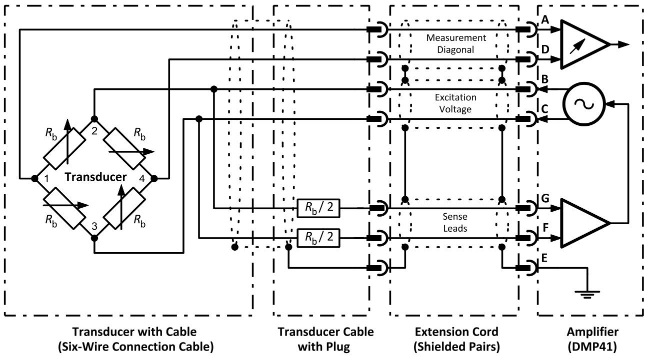

Figure 9: Transducer connection with matching resistors (six-wire)

It should be mentioned at this point that an incompatibility can occur with 0-wire TEDS modules (Transducer Electronic Data Sheet). The 0-wire TEDS modules use the sense line for data transmission. TEDS modules with 0-wire circuit already include 100 Ω matching resistors.

An increase by an additional resistor in series is possible only between the sensor and the TEDS module. The impedance may not be increased between the TEDS module and amplifier. Due to the higher impedance of the sense leads by adding additional matching resistors, the activation current for the 0-wire TEDS module may not be sufficient.

The 1-wire TEDS modules are not affected, because they are controlled by a separate wire. However, these do not work through the additionally required line with six-core extension cords.

5. MEASUREMENT RESULTS

The impact of an interconnected extension cable can be completely eliminated by wiring the transducer as described above. The significant improvements of the six-wire-circuitry combined with matching resistors lead to unaffected DMP41 results. Figure 10 shows the dependence of the measuring error of a 350 Ω transducer with and without matching resistors $R_b/2$ as a function of cable length l_c.

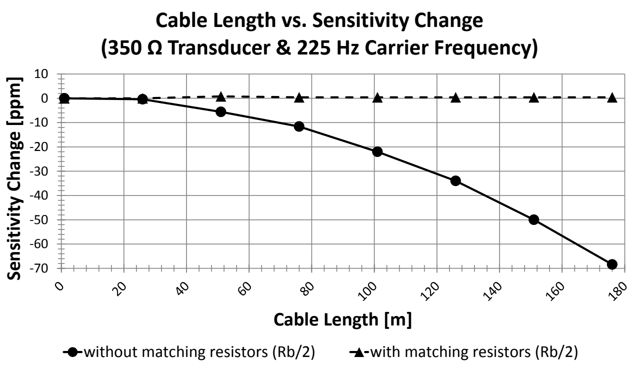

Figure 10: Measured sensitivity change depending for 350 Ω

For this measurement, the cable length was varied between the bridge calibration unit BN100A and the measuring amplifier DMP41. Furthermore, the measurement cable described above was used. The effect of this error for the DMP41 and a 350 Ω Transducer can be approximated by a quadratic regression (6).

$$\Delta V_c = (-0.0023\, l_c^2 + 0.0170\, l_c + 0.1520)\ \mathrm{ppm} \tag{6}$$

Without matching resistors the class accuracy of the measuring amplifier will be left above a cable length of 50 m. By using adequate matching resistors there is no error anymore, even with a cable length of more than 180 m. The behavior for transducers with higher impedance or amplifiers with higher carrier frequencies is similar, but much worse. Figure 11 shows the sensitivity change for a 4 kΩ transducer. This and the measurement before differ to the calculation from the beginning. This is due to the maximum specification of the cable parameters, the simplification of the transmission function of the cable and the neglected input impedance of the amplifier.

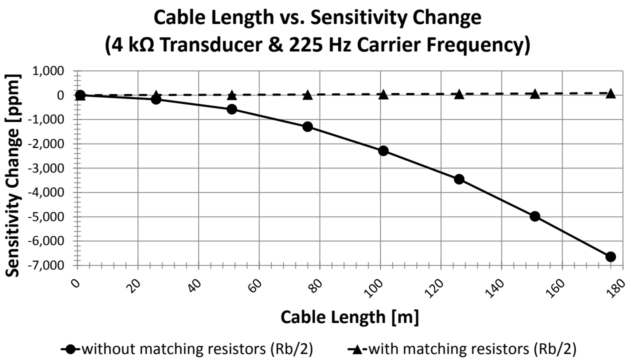

Figure 11: Measured sensitivity change depending for 4 kΩ

However, using this principle will not eliminate the very low residual errors during measurements. These are caused by the value differences due to manufacturing tolerances. The two cable pairs can slightly differ in terms of the capacity and copper resistance. In the experiment, the residual error could be reduced to zero without adjusting the matching resistors.

6. CONCLUSIONS

For accurate measurements of transducers based on strain gauge technology precision amplifiers are necessary. If the amplifier is much more accurate than the transducer itself, then the measurement uncertainty of the amplifier can be neglected [14].

If some fundamentals are not taken into account, errors higher than the class accuracy can occur due to the transducer extension cords. These errors were shown in simplified form and an order of magnitude was given therefore. This was confirmed by a practical measurement, using a precision instrumentation amplifier. With additional adjustment resistors cables dependent errors can be completely eliminated in DMP41 for 350 Ω transducers.

For precision measurements in the ppm range not only a highly accurate measuring amplifier is necessary, it is also important to use an appropriate measuring cable combined with proper matching resistors. This is often underestimated by the user.

7. REFERENCES

[1] Schäck, M.: *"High-Precision Measurements of Strain Gauge Transducers"*, Proceedings of TC22 International Conferences IMEKO Congress, Cape Town, Republic of South Africa, 2014

[2] Schäck, M.; Kitzing, H.: *"Messverstärker mit Hintergrundjustierung und Verfahren dafür"*, DE 10 2013 014 876 B3, German Patent and Trade Mark Office, Munich, Germany, 2014

[3] Heringhaus, E.; *"Trägerfrequenz- und Gleichspannungs-Meßverstärker für das Messen mechanischer Größen - ein Systemvergleich aus anwendungstechnischer Sicht - Teil 1: Arbeitsweisen und Vergleich charakteristischer Eigenschaften",* Messtechnische Briefe (HBM) issue 18, Darmstadt, Germany, 1982, pp. 42-49

[4] Hoffmann, K.: *"An Introduction to Measurements using Strain Gages"*, HBM, Darmstadt, Germany, 1989, pp. 171-179

[5] Clausert, H.; Wiesemann, G.: *"Grundgebiete der Elektrotechnik 2"*, Oldenburg Wissenschaftsverlage GmbH, Germany, 2000, pp. 202-218

[6] Heringhaus, E.; *"Trägerfrequenz- und Gleichspannungs-Meßverstärker für das Messen mechanischer Größen - ein Systemvergleich aus anwendungstechnischer Sicht - Teil 2: Verhalten gegenüber externen Störeinflüssen und praktische Auswahlhilfen",* Messtechnische Briefe (HBM) issue 18, Darmstadt, Germany, 1982, pp. 70-73

[7] Hottinger Baldwin Messtechnik GmbH.: *"Ausführung und Anschluss von HBM-Meßkabeln",* Messtechnische Briefe (HBM) issue 1, Darmstadt, Germany, 1970, pp. Binding

[8] Riedhof, D.: *"Zur Referenzphaseneinstellung bei Trägerfrequenz-Meßversträrkern",* Messtechnische Briefe (HBM) issue 10, Darmstadt, Germany, 1974, pp. 8-10

[9] Rafflenbeul, L.; Schäck, M; Werthschützky, R.: *"Optimization of the input impedance of a low-noise unipolar powered amplifier"*, Proceedings of Eurosensors XXV, Athens, Greece, 2011

[10] Schäfer, A.; *"The Ultra-Precision Instrument DMP41 - First Experiences & Appropriate Filter Settings"*; Proceedings of TC22 International Conferences IMEKO Congress, Cape Town, Republic of South Africa, 2014

[11] Kreuzer, M.: *"Die Schnittstelle zwischen Aufnehmer und Messverstärker bei Gleichspannung und Trägerfrequenzspeisung"*, Messtechnische Briefe (HBM) issue 26, Darmstadt, Germany, 1990, pp. 42-48

[12] Kreuzer, M.: *"Kalibrieren des Digitalen Präzisions-Meßgeräts DMP39 mit einem speziellen Brückennormal"*, Messtechnische Briefe (HBM) issue 17, Darmstadt, Germany, 1981, pp. 67-73

[13] Kreuzer, M.: *"High-precision measuring technique for strain gauge transducers"*, Internal publication of Hottinger Baldwin Messtechnik GmbH, Darmstadt, Germany, 1999

[14] Schäfer, A.; Kitzing, H.: *"DMP41 - A new chapter of ultra-precision instrument for strain gauge transducers"*, Proceedings of XX IMEKO World Congress, Busan, Rep. of Korea, 2012