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A SOLID BASE FOR PRECISION STRAIN GAUGE MEASUREMENTS

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Abstract: The producer of high-precision measurement equipment for strain gauges has to guarantee that the physical unit mV/V is to be presented exact, stable, but also easy to use. This is achieved by means of calibration standards, which are checked regularly by the PTB. A further certainty is attained through company-internal comparisons.

In the following will be shown which technical conditions and limits are to be observed, and which problems are arising, if one wants to reach transferable results down to some ppm.

Keywords: strain gauge, precision measurement

1 WHAT IS A PPM?

In high resolution measurements often the unit „ppm“ or „part per million“ is used. To realize what one part per million means, here are some practical examples:

1 ppm of the distance Vienna – Amsterdam is 1.10 m
1 ppm of a year is half a minute
1 ppm of the way to the moon is 400 m
1 ppm of a ton is 1g

The test equipment we will discuss, has an accuracy class of 5ppm. This means that the linearity error and long term drift (over 10 years) are below 5ppm; the effect of the temperature to the zero point drift or span drift is lower than 5ppm/10K.

2 THE CHAIN OF CALIBRATION

Every company receiving certification in accordance to ISO 9000 must prove traceability to National standards. The aim of the traceability requirement is to guarantee correct measurement. The term calibration means the comparison with a reference. This reference has to be calibrated itself in an unbroken line of succession back as far as the National standard. Depending on the level in this traceability chain, the reference is called „National standard“ (in Germany exclusive to the PTB), a „Reference Standard“ in the German Calibration Service (Deutscher Kalibrierdienst – DKD), or a „Working Standard“, i.e. the test equipment in a calibration laboratory. In the following will be shown how a working standard for the unit „mV/V“ is built and which accuracy and stability can be achieved.

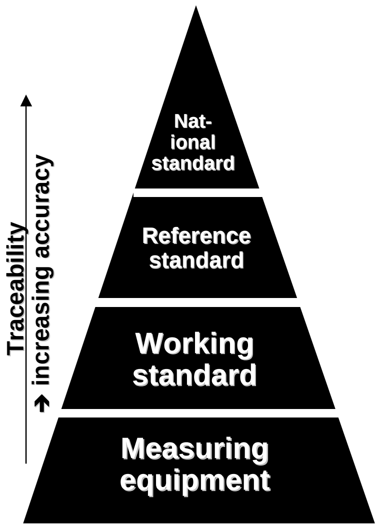

Figure 1.

3 HIGH PRECISION STRAIN GAUGE MEASUREMENT TECHNIQUE

The precision transducers use strain gauge full bridges. Every strain gauge has typically 350 Ω resistance, so a full bridge with four elements will have 350 Ω too. The output signal of such a bridge reaches only 2 mV/V. To have a high electrical signal, one could think to use a high supply voltage; but this results in high power in the transducer, which means a warm up and problems with the stability of the transducer. So the normally used supply voltage is 10 V or 5 V (280 mW or 70 mW in a 350 Ω transducer).

The supply voltage has to be brought to the transducer with cables of copper, which have, even if we choose very thick cables, a considerable ohmic resistance. This will drop the supply voltage resulting in a loss of sensitivity. There is an interesting calculation: To avoid sensitivity losses of more than 5 ppm, the length of the transducer cable must not exceed some millimeters! This is not tolerable, we need cable length of some meters. And furthermore, the resistance of the copper is changing with temperature; this will alter the effective supply voltage of the transducer and so result in a change of sensitivity. So it is easy to see that it not possible to calibrate a transducer to the desired accuracy with a 4-wire cable.

The solution of the problem is the use of sense lines: the voltage directly at the transducer is fed back to the amplifier. Because these sense lines are not leading any current, the cable resistance gives no voltage drops. A control loop in the amplifier increases the supply voltage, until the sense lines and therefore the full bridge have the correct voltage; so the loss of the cable is compensated. Now the sensitivity of the transducer can be hold stable even with cables of 100m and more. Every precision strain gauge amplifier uses sense lines; this type of connection is called „6-Wire-Technique“.

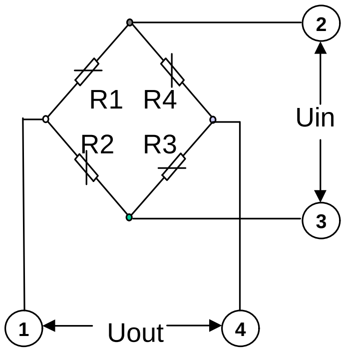

Figure 2.

The signals from the transducer are small, with 5 V supply and 2 mV/V sensitivity we have only 10 mV signal (full scale!). Because we want a resolution up to 1,000,000 parts, we need a resolution of 10 nV at the input. Therefore we have to consider thermal voltages, which arise on every connection of different materials with different temperatures. In practice it is not possible to avoid any connections or to keep them at the same temperature; the material of the wires will be copper, of the strain gauges it is constantan. One degree temperature difference will result in about 42 µV of thermal voltage, and only 1/100 °C difference still makes 400 nV or 40 digits in our display.

The solution is to use carrier frequency: as supply voltage is not a DC voltage used, but a AC voltage of typically 225Hz sinus. This will suppress any DC signals from the transducer. The synchronous demodulation in the amplifier works like a narrow filter around the carrier frequency. So not only the DC-area, but also any disturbance from the line frequency is suppressed. The excitation voltage is balanced to ground so that the input voltage has nearly no DC-offset. This makes the input stage easier, and we don't need a good and very expensive DC-stable (10 nV !) amplifier input.

The selection of the very low carrier frequency is made to avoid influence of capacities in the cable and the transducer. A good solution is here to use a cable with three pairs of shielded cores to avoid coupling between excitation and input lines.

DMP40

Resolution	**2 000 000 digital steps**
Linearity error	**< 5 ppm**
Zero point drift	**< 5 ppm / 10° C**
Span drift	**< 5 ppm / 10° C**
Long-term drift	**< 5 ppm / 10 years**

Figure 3. Amplifier for High Precision Strain Gauge Transducers

A last point worth mentioning is noise: the strain gauges in the transducer produce thermal noise just as any resistor. The formula shows the influence of temperature, resistance and bandwidth. We can't lower the temperature, and even with lower resistors we will have no success: to keep the same output voltage, we would have to keep the supply voltage, increasing the current and the power in the transducer. Therefore the only thing we can do is to reduce the bandwidth. This leads to a trade-off between frequency range and resolution. As a rule of thumb, to reach one million parts resolution at a supply voltage of 10 V, the bandwidth is limited to 1 Hz. And this limitation comes only from the strain gauges, assuming an ideal amplifier, which will not add any own noise.

$$V_{rms} = \sqrt{4 \cdot k \cdot T \cdot R \cdot B}$$

V_{rms}	=	**Root Mean Square Noise Voltage**
k	=	**Boltzmann Constant (1.380662 × 10^{-23} J/K)**
T	=	**Absolute Temperature in K**
R	=	**Resistance in Ω**
B	=	**Bandwidth in Hz**

Figure 4.

4 REPRESENTATION OF THE UNIT „mV/V“

To be able to test, adjust or verify the amplifier equipment for high precision strain gauge transducer we need a working standard, a calibration standard for the voltage ratio, the unit mV/V.

The relation of output voltage to supply voltage is represented through a „divider“; typically the division factor is 500 for 2 mV/V. This relation has to be very precise, stable, but also easy to produce. The easiest way to construct such a divider would use two resistors. But the results would be very poor, this divider would not have the same input- and output-impedance of a strain gauge full bridge. And the tracking of the temperature coefficient of the resistors is a problem, when the absolute values of the resistor of such different size.

A better solution could be a full bridge made out of four stable 350 Ω resistors. If they exactly match, the output will be 0 mV/V, input- and output impedance are 350 Ω too. To achieve an output signal of 2 mV/V, one can use a shunt resistor (app. 43 kΩ) or two shunt resistors (each app. 86 kΩ). With high precision resistors it is possible to yield a stability of 50ppm or even 25 ppm; the main problems will be the temperature coefficient and the long term stability.

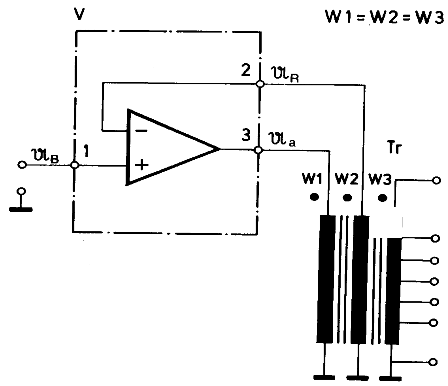

Figure 5. Inductive Divider with Electronic Circuit for Error Correction

But there is another, better solution: because we use carrier frequency, we can use an inductive divider, which in fact is a special transformer: If constructed with care, the relation of output to input is only depending on the number of windings; and this is very long time stable. There are two problems with the optimal technical realization: the magnetic flux in the primary and secondary winding must be the same; this is achieved with a relatively large core and twisted wires. Than we have the loss through the copper resistance and the low input impedance: both can be solved with the shown electronic error correction. We use a third winding as a sensor. The amplifier has a high impedance input with no load for the input and will produce an output so, that the voltage from winding 2 is exactly the same as the input. If the load on the output w3 is not too low, we will have a nearly ideal transformer.

Another advantage of this transformer is the possibility to use taps. The output winding w3 can be split in ten equal parts, which will give absolute linear steps of 10 percent. So we can not only check the span of an amplifier, but also the linearity and symmetry at some points.

With these considerations we can come to the realization of an inductive calibration unit. We use not only one divider, but three decadic steps to cover a wide range of mV/V values. The input stage provides a constant ohmic load of 350 Ω. The second purpose of this stage is to convert from symmetrical input signals to a grounded signal; because of the same count of all windings we come to 500mV/V at the output of transformer 1. With the switch S1 we can change the polarity of the generated output signal from plus to minus, so we can examine the symmetry of the tested amplifier.

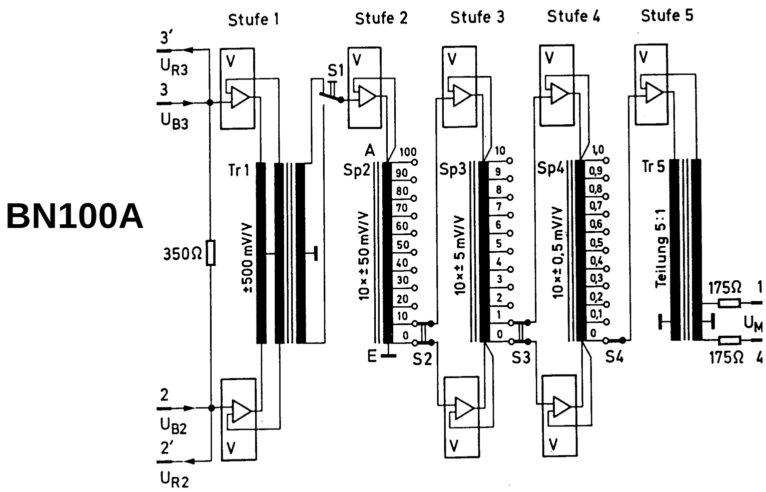

Figure 6. Block Diagram of an Inductive Calibration Unit

The next stage is a divider with 11 tabs, so the difference between each two tabs is 50 mV/V. Now we have to look for two ways: the difference, independent of the position of the selector S2, is routed to the next stage and divided further. But the lower tab is routed to the bottom of the next divider, and makes an offset. The same is done in the following stage, and the last stage is a divider by 5. The two output resistors of 175 Ω gives an output impedance of 350 Ω.

In the input and between all stages we use operational amplifiers to have very high input impedance and no load to the stage before. To understand the operation, it would be best to start with all selectors switched to zero, and the output will be zero too. When S2 now is switched to the first position ("10"), 500 mV/V divided by 10 is routed to stage 3 as offset, and than again to stage 4, then divided by 5, so we get 10 mV/V. When selector S3 is moved to the position "1", the bottom point of stage 4 is moved to 50 mV/V plus 5 mV/V, after the last stage we have 11 mV/V. With the three selectors we can reach +-100 mV/V with steps of 0.1 mV/V. This will cover the complete input range of the shown high precision amplifier.

Figure 7. Calibration Unit **BN100A**

The electronic elements inside the calibration unit are used to compensate all side effects like losses in the transformers. But the accuracy and stability is determined nearly exclusive by the inductive components.

The input voltage is limited to 10 Veff, because the internal used amplifiers should not clip. The input and output impedance is defined by resistors of 350 Ω, the excitation voltage must be 225 Hz, and of course a 6-wire-cable with three different shields is to be used. The length of this fixed to 1.5m. Under these conditions the BN100A is a perfect simulation of a strain gauge full bridge, with an extreme stability.

The predecessor of the BN100A, the BN100 with nearly the same electrical specification was developed together with the amplifier DMP39 nearly 20 years ago. Two units of the BN100 were calibrated by the PTB in Braunschweig. We received the certification as a Reference Standard in 1989. These two units were checked regularly against other units and amplifiers over the years. The picture shows the outstanding stability: all measurement results are in a band of +-2ppm.

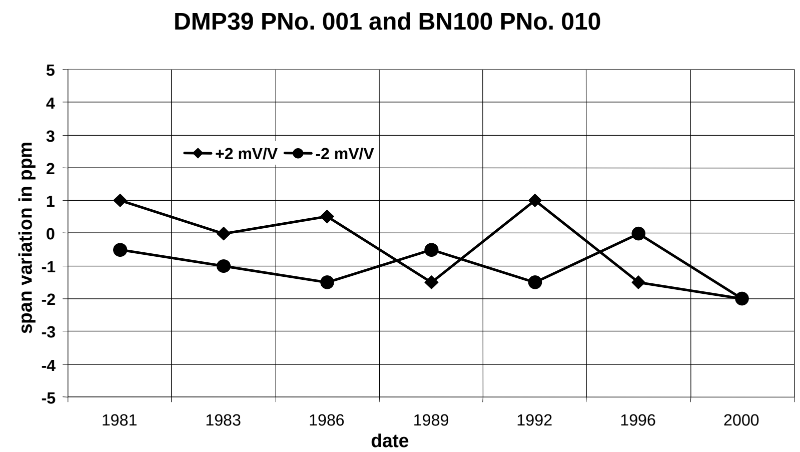

Figure 8. Long-term Stability

The accuracy class for the Reference Standard is 10 ppm at 10 V and 20 ppm at 5 V excitation voltage.

In the last 10 years over hundred BN100's and BN100A's were build. Most of them have a DKD calibration certificate and are traceable Working Standards. They serve in the manufacturing of precision amplifiers as well as in the field for checking these amplifiers. The device is easy and clear to use, the weight and size are small enough to transport it all over the world to verify the mV/V unit. The outstanding stability gives a solid base for high precision strain gauge measurements.

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