Calibration of bridge standards for use in strain-gage measurements

by Günther Ramm

Within the field of stress analysis the signal provided by the measuring element, usually a strain gage bridge, is normally at a low level not exceeding a few millivolts. This signal must therefore be amplified with a calibrated amplifier before it can be recorded. A common method of calibrating the amplifier system prior to using it for measurement is to substitute the strain gage bridge with a bridge standard which supplies an accurate signal. Obviously the accuracy of the bridge standard itself is a critical feature in the whole process. This article describes the method used for accuracy tests made on the BN 100 Bridge Calibration Unit.

Introduction

Voltage ratios as an electrical measurement quantity are important in numerous fields of precision measurement. Resistance, capacitance and inductance ratios can be determined as voltage ratios using bridge circuits. Using the parameters mentioned, it is in turn possible to take measurements of temperature, angle, length, strain, force, pressure and torque by obtaining voltage ratios. This article takes a closer look at the measurement of the voltage ratios which are important in the application of strain gages.

A strain gage's resistance value changes as a result of mechanical loading. If a combination of strain gages are used to form a bridge circuit which is then supplied with an electrical voltage, then the ratio of the bridge output voltage to the bridge supply voltage changes in relationship to the mechanical loading. Depending on the design of the transducer containing the bridge circuit, the mechanical quantity, e.g. strain, force, pressure or torque, is then represented as an electrical voltage ratio. Due to the limited strain region of strain gages, the voltage ratio is therefore also small. In practical measurements values of up to $2 \cdot 10^{-3}$ or 2 mV/V are very common.

The electrical measurement instrument connected to the transducer then displays the voltage ratio formed by the strain gage bridge circuit. In order to calibrate the measurement instrument, the transducer or the strain gage bridge circuit is replaced by a "bridge standard". This method enables defined voltage ratios to be displayed and applied to the measurement instrument on a purely electrical basis, i.e. without any mechanical influence. Bridge standards include either resistance dividers or transformers. The former are suitable for both d.c. and a.c. applications, whereas the latter can only be used with a.c. methods. Within the scope of a research project agreed between HBM and the Physikalisch-Technische Bundesanstalt (PTB) [1], the error characteristics of a transformer bridge standard of the type BN 100 were investigated. The measurement equipment used by the PTB for this investigation could measure voltage ratios of 2 mV/V with a relative uncertainty of only $5 \cdot 10^{-6}$ at a frequency of 225 Hz and it is presented here with some examples of the measurement results.

Main design features of a strain gage measuring system

Figure 1 shows a diagram of an electrical circuit for a force measurement system, consisting of a transducer

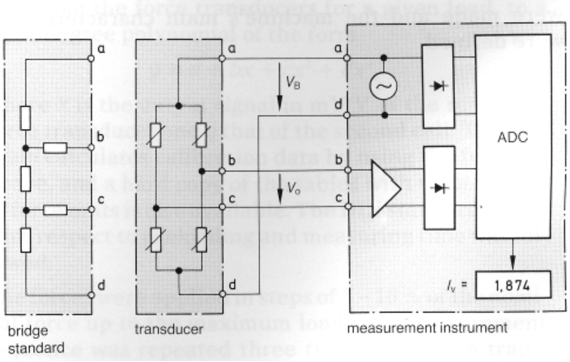

Fig. 1: Diagram of a force measurement system, consisting of a transducer and measurement instrument. Left: a bridge standard which can be substituted for the transducer for calibration purposes

and a measurement instrument. This illustration can be used to explain the principle of measurement equipment operating on the strain gage principle. The ratio of the bridge supply voltage V_B and the output voltage V_0 for a force transducer is proportional to the applied force F:

$$V_o/V_B = K_1 F. \tag{1}$$

The measuring instrument supplies the supply voltage for the force transducer and amplifies its output voltage. The measurement value I, which is proportional to the voltage ratio V_0/V_B, is formed using an analog-digital converter ADC:

$$I_v = K_2 \cdot V_o/V_B. \tag{2}$$

The relationship between the measured force and the output measurement value for the force measurement system can be obtained from equations (1) and (2):

$$I_v = K_1 K_2 F \tag{3}$$

The force transducer is disconnected for the electrical calibration of the measurement instrument and it is replaced, as shown in **Fig. 1**, with a bridge standard. Defined ratios of output voltage V_0 and supply voltage V_B can be set up with high accuracy using bridge standards [2]. The transfer factor K_2 of the measurement unit is calibrated with the signal provided. The voltage ratio

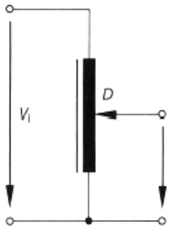

Fig. 2: Inductive voltage divider IVD with adjustable transfer ratio *D*

$$V_o/V_B = 0.002 = 2\,\mathrm{mV/V}$$

is the most commonly used calibration signal. A measurement technique for examining this calibration signal is presented below.

Measurement equipment

Principle

Using inductive voltage dividers (IVDs), it is possible to obtain very accurate readings of a.c. voltage ratios which are largely independent of temperature and stable over a long period of time [3,4,5]. **Figure 2** shows the principle of an adjustable voltage divider. If *D is* the transfer ratio possessing an uncertainty of *u*, then the ratio of the output voltage V_0 to the input voltage V_i on the voltage divider is

$$V_o/V_i = D \pm u \tag{4}$$

The range of values for *D is* between zero and one. Precision IVDs include seven or eight decades producing a resolution in the transfer ratio of 10^{-7} or 10^{-8}.

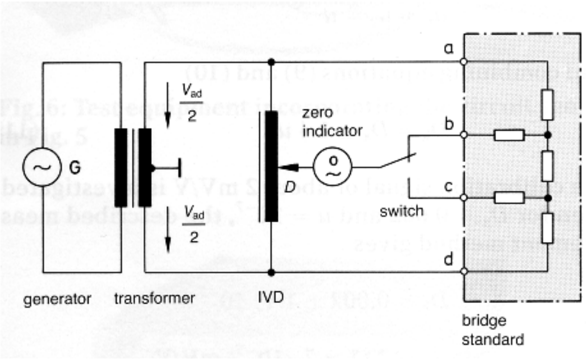

Fig. 3: Measurement principle for calibrating bridge standards

At a measurement frequency of 225 Hz, figures of $u = 1 \cdot 10^{-7}$ can be achieved (all uncertainty figures in this article refer to a confidence level of 95 %).

With inductive voltage dividers the input and output voltages are referred to a common connection which is normally at ground potential. In contrast, bridge calibration units are supplied with a voltage located symmetrically about ground potential and they produce a similarly located voltage. Using the circuit illustrated in **Fig. 3**, the voltage ratio

$$V_{bc}/V_{ad} = D_k \tag{5}$$

of a symmetrically supplied bridge standard can be compared with the transfer ratio *D* of an IVD. The transformer, which has its primary winding connected to the generator and its secondary winding grounded at the center, symmetrizes the input voltage V_{ad}. The inputs of the IVD and of the bridge standard are wired in parallel. The switch position b for the transfer ratio *D is* now changed while observing the zero indicator until the divider output is equal to the voltage V_{bd}. Then the following equation applies

$$V_{bd}/V_{ad} = D_b \pm u_b. \tag{6}$$

A second balance point for switch position *c* gives

$$V_{cd}/V_{ad} = D_c \pm u_c. \tag{7}$$

The difference between equations (6) and (7) produces the voltage ratio defined in equation (5) for the symmetrically fed bridge standard in the form

$$D_k = V_{bd}/V_{ad} - V_{cd}/V_{ad} \tag{8}$$

and

$$D_k = D_b - D_c \pm u_b \pm u_c \tag{9}$$

$$D_k = D_x \pm u_x$$

The total uncertainty u_X is derived as the square root of the sum of squares of the parts u_b and u_C:

$$u_x = \sqrt{u_b^2 + u_c^2}. \tag{10}$$

Putting

$$u_b = u_c = u$$

and combining equations (9) and (10)

$$D_k = D_x \pm 1.4\, u. \tag{11}$$

If a calibration signal of about 2 mV/V is investigated, then for $D_X = 0.002$ and $u = 10^{-7}$, the described measurement method gives

$$D_k = 0.002 \pm 1.4 \cdot 10^{-7}$$

$$= 2\,(1 \pm 7 \cdot 10^{-5})\ \text{mV/V}.$$

Recently, technical development has led to applications where a relative uncertainty of 7 · 10^{-5} is too large for the determination of calibration signals at about 2 mV/V. The following shows how this uncertainty can be reduced.

Special measurement equipment for calibration signals of 2 mV/V

To reduce the measurement uncertainty, special measurement equipment was developed; the operating principle is shown in **Fig. 4**. The circuit illustrated in **Fig. 3** was extended with a second inductive voltage divider IVD2 which gives two fixed voltage ratios D_{21} and D_{22}, symmetrical about the center. On the following adjustable IVD1, only a small part of the calibration unit's input voltage V_{ad} appears. A high resolution is now possible. As in the circuit in **Fig. 3,** two balancing processes are undertaken in the switch positions b and c. First of all, without considering the uncertainties, the following relationships are obtained:

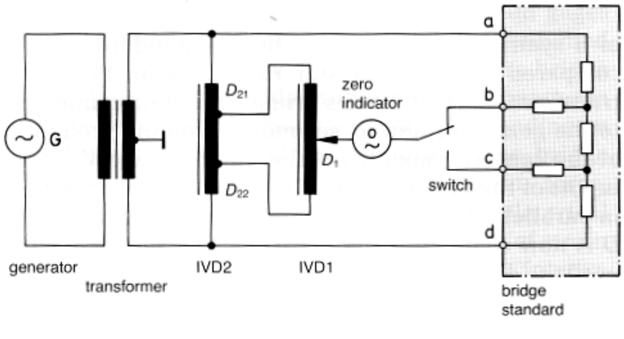

Fig. 4: Principle of the special measurement equipment for calibration signals at about 2 mV/V with a voltage divider IVD1 having an adjustable transfer ratio and a second voltage divider IVD2 with two fixed symmetrical tappings

$$V_{bd}/V_{ad} = D_{22} + (D_{21} - D_{22}) \cdot D_{1b} \tag{12}$$

$$V_{cd}/V_{ad} = D_{22} + (D_{21} - D_{22}) \cdot D_{1c} \tag{13}$$

The difference gives

$$D_x = (D_{21} - D_{22}) \cdot (D_{1b} - D_{1c}) \tag{14}$$

The uncertainties in the transfer ratios D_{21}, D_{22}, D_{1b} and D_{1c} are

$$u_{21} = u_{22} = u_{1b} = u_{1c} = u.$$

The voltage ratio D_k for the symmetrical bridge standard can be derived from the above equations, neglecting products of small quantities [1]:

$$D_k = D_1 \cdot D_2 \pm 1.4 \cdot u \cdot \sqrt{D_1^2 + D_2^2} \tag{15}$$

The calibration signal used is again 2 mV/V so that $D_x = D_1 - D_2 = 0.002$. This condition can be satisfied with various combinations of D_1 and D_2. The choice of D_1 and D_2 affects the uncertainty u_x. In any case the uncertainty is reduced in comparison to equation (11) by the factor $(D_1^2 + D_2^2)^{0.5}$. The smallest uncertainty is obtained for $D_1 = D_2 = \sqrt{D_x}$ with $u_x = 0.04472\ldots$ [1]. This value can be approximately obtained on the adjustable IVD1, but it is not suitable for the measurements to be carried out, because of the fixed transfer ratio of $D2$ on IVD2. D_2 was selected as 0.04. D_1 is then 0.05. Putting $u = 10^{-7}$, equation (15) gives

$$D_k = 0.002 \pm 1 \cdot 10^{-8} = 2\,(1 \pm 5 \cdot 10^{-6})\ \text{mV/V}. \tag{16}$$

The result shows that voltage ratios around 2 mV/V can be determined using the described measuring equipment with a relative uncertainty of only 5 · 10^{-6}. Compared with the circuit illustrated in **Fig. 3**, the uncertainty was reduced by a factor of 14. This improvement was achieved using two inductive voltage dividers wired in cascade. Another advantage of this circuit is the substantial increase in resolution compared to previous methods.

The requirements for achieving this low figure for the circuit's uncertainty are the implementation of the inductive voltage dividers as two-core transformers [4] with magnetizing winding, the use of shielding and twisting of all the wires and the six-wire circuit configuration for the bridge standard.

If an eight decade inductive divider is used for IVD1, the resolution of the measurement equipment is 0.4 · 10^{-6} mV/V. With an input voltage of V_{ad} = 5 V, the voltage on the divider output can be altered in steps of 2 nV! This high resolution can only be fully utilized at low input voltages if a zero indicator is used with a low-noise preamplifier [6].

Circuit details

The basic measurement circuit, shown in **Fig. 4**, for calibrating the bridge calibration unit is illustrated in more detail in **Figure 5** with particular emphasis on the range 0 mV/V to ± 2 mV/V. The second inductive voltage divider is constructed according to the two-core technique. It contains the magnetizing windings W_{m1} and W_{m2} as well as the ratio winding W_d with two fixed tappings symmetrical about the center. The ratio winding divides the feedback voltage by a factor of 40 and supplies the following eight-decade adjustable divider, IVD1. In order to avoid overloading IVD2 due to the load presented by IVD 1, IVD2 has an additional winding, W_{m1}. The sole task of W_{m1} is to supply the magnetization winding W_m in IVD1.

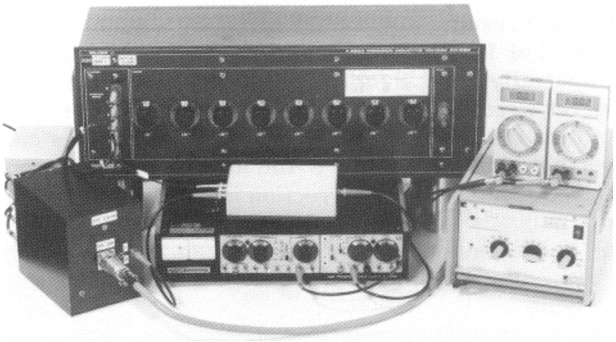

Fig. 6: Test equipment incorporating the circuit shown in Fig. 5

Figure 6 shows a photograph of the equipment incorporating the measurement circuit in **Fig. 5**. The transformer Tr1 can be seen in the background with the eight-decade adjustable inductive voltage divider IVD1. From left to right are the inductive voltage divider IVD2, the zero indicator with the transformer Tr2 on top and the BN 100 Bridge Calibration Unit with the two digital multimeters for indicating the output voltage of the zero indicator.

BN 100 error characteristics

General remarks

The BN 100 Bridge Calibration Unit provides a simulation of the output voltage from 350 ohm full-bridge strain-gage transducers. The nominal output voltage referred to the input voltage can be adjusted in a range from ± 100 mV/V using a polarity switch and three rotary switches with decade stages of 10 mV/V, 1 mV/V and 0.1 mV/V. These switches can be seen on **Fig. 7**, which shows the front panel of the BN 100.

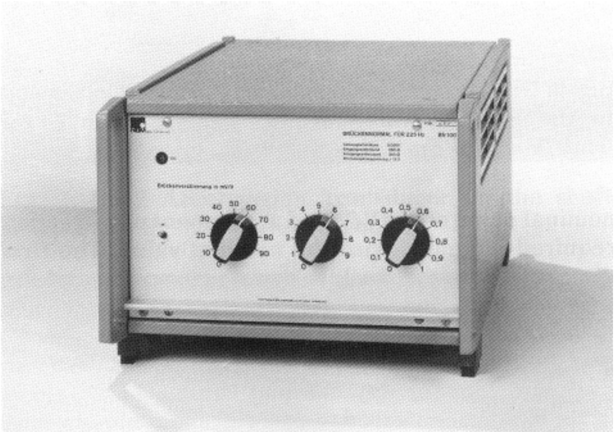

Fig. 7: The BN 100 Bridge Calibration Unit

For the measurements, the BN 100 was connected to the measurement equipment in a six-wire configuration via the supplied measurement cable of length l_C with an equipment socket on the end. The bridge excitation voltage which is symmetrical about ground was applied to pins B and C of this equipment socket. The voltage between pins A and D was used as the output voltage. Pin E was grounded. The designation of the pins selected here corresponds to those on the cable plug and on the socket Bu 1 at the back of the BN 100.

The measurement is the quotient of the real part of the output voltage (in phase with the part applied to the input voltage) and the input voltage itself. Measurements were made using a sinusoidal alternating voltage of 225 Hz frequency at input voltages V; of 2.5 V, 5 V, 7.5 V, 10 V and 12.5 V with various connecting cables l_C, of 0.3 m, 3 m and 6 m. The more significant results are given in the following sections. A complete summary of all the test results are given in [1].

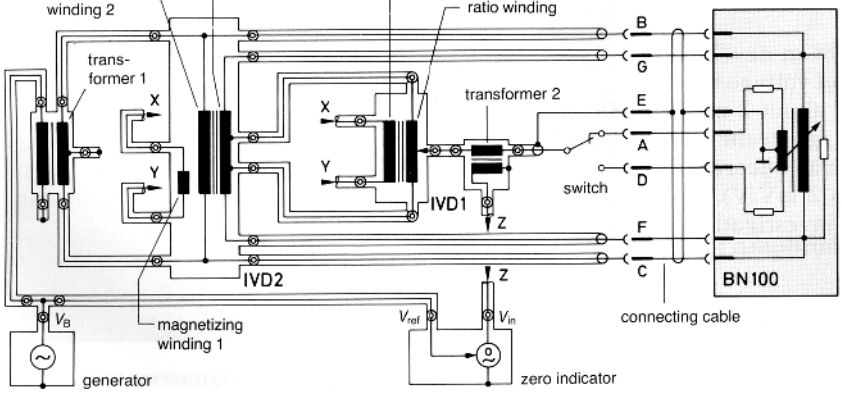

Fig. 5: Detailed diagram of the test circuit shown in Fig. 4 for calibration of the BN 100 Bridge Calibration Unit in the range between 0 mV/V and ± 2 mV/V

Test results

The test results, which were found with an input voltage V_i of 10 V and a cable length of 3 m, are shown graphically in **Fig. 8** for 0 mV/V $\leq D \leq 2$ mV/V. Similar curves were also recorded for 0 mV/V $\leq D \leq 20$ mV/V and for 0 mV/V $\leq D \leq$ 100 mV/V. Two features are worth noting: in contrast to the ideal case (all corrections equal to zero), a correction is required even at a nominal value of 0 mV/V and the amount of correction required increases with the nominal value. The first effect can be described as a zero-point error and the second effect can be interpreted as scaling or gain error. The scaling error can be estimated by subtracting the correction for the nominal value 0 mV/V from the correction for any nominal value. The resulting value *K'* is then referred to the relevant nominal value. The *K'* values are equal in magnitude within the respective uncertainty ranges for the pairs of nominal values ± 100 mV/V, ± 20 mV/V and ± 2 mV/V. It can therefore be stated that the polarity switch does not produce any serious errors due to the polarity change. The following information is provided by **Fig. 8**: if the corrections for the nominal values of 0 mV/V and 2 mV/V are joined, then all other corrections are located less than $\pm 10 \cdot 10^{-6}$ mV/V, respectively $\pm 5 \cdot 10^{-6}$ (referred to 2 mV/V) from this imaginary line. The linearity is then better than $\pm 5 \cdot 10^{-6}$. These statements only however apply for the actual measured nominal values.

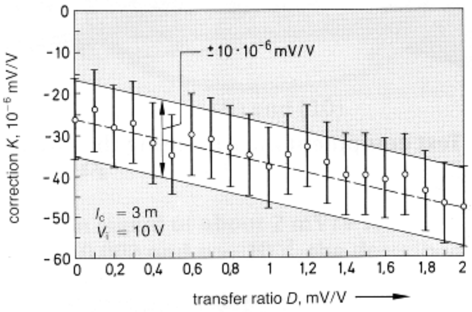

Fig. 8: Graph showing the corrections *K* in relationship to the nominal value of the transfer ratio *D* for 0 mV/V ≤ *D* ≤ 2 mV/V

Summary

Special measurement equipment has been developed and constructed for the measurement of voltage ratios in the mV/V region. Voltage ratios of about 2 mV/V, which occur particularly frequently in strain gage measurements, can be determined with an uncertainty of only $5 \cdot 10^{-6}$ (relative, referred to 2 mV/V). This measurement equipment enables the investigation of the error characteristics of the BN 100 Bridge Calibration Unit which provides a simulation of full-bridge strain-gage transducers.

The results for the particularly interesting range of 0 mV/V to 2 mV/V can be summarized as follows: The unit has a zero-point error. If this is then eliminated by computation, the measurement for 2 mV/V is about $11.5 \cdot 10^{-6}$ (relative, referred to 2 mV/V) lower than the nominal value. The linearity of the BN 100 in this region is better than $\pm 10 \cdot 10^{-6}$ mV/V or $\pm 5 \cdot 10^{-6}$, referred to 2 mV/V. The measurements in this region are hardly influenced at all by the length of the connecting cable or the level of the input voltage and all the changes found are located within the measurement uncertainty.

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