

# HOW TO AVOID ERRORS CAUSED BY HEAT EFFECTS IN STRAIN GAGE MEASUREMENTS WHEN USING SCANNING UNITS

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Excitation voltages applied to strain gages cause heat effects which may produce signal changes and measuring errors. This paper shows the most important results of many measurements which had to be taken to determine the amplitudes and time constants of these shifts of signals for different strain gage types, excitation voltages, adhesives and construction materials. In its second part the paper discusses methods of avoiding measuring errors due to heat effects and describes a scanning unit which allows to take measurements almost insensitive towards heat effects, voltage drops across the measuring leads and switching elements, or induced error voltages.

## 1. INTRODUCTION

If many strain gage signals are to be measured, scanning units usually do this job. These scanning units normally contain only one central measuring amplifier and signal conditioning unit which is connected to individual strain gages one by one using highly sophisticated switching circuits. This is quite difficult because errors due to voltage drops produced by switch- and wire-resistances must be avoided. This feat is especially difficult to accomplish when applying strain gages in half- and quarter-bridge circuits because changes in measured resistances are extremely small. The paper shows how to design switching circuits, so that voltage drops across the measuring leads and switching elements cannot falsify the readings. Since the individual measuring points are switched one by one, the excitation voltage supplies the strain gages only during measurement. Therefore, the temperatures of the strain gages do not increase significantly. This is especially important if strain gages are adhered to plastic, wood or other materials with low thermal conductivity. Heat effects cannot be neglected completely, however, because the signals dependent on temperature change very rapidly immediately after exciting the strain gages. So if measuring time varies, the readings may also vary significantly. There are several reasons why the measuring time may vary. High scanning rates and high signal resolution cannot be achieved simultaneously. To get stable strain gage measurements with high resolution, the strain gage signals have to be integrated for an extended time period, e.g. 100 ms. But 100 ms is about 4 times the thermal heat-up time constant of a medium sized strain gage adhered to a steel test object.

Thus, the readings obtained when working with higher scanning rates ( $> 40 \text{ s}^{-1}$ ) will differ from the readings obtained when

working with lower scanning rates and extended integration times. So, if scanning rates are lowered and integration time increases, you do not only get higher resolution but also changing measurements as a negative result. Most scanning units provide an automatic zero balancing facility. It may occur that measuring values taken immediately after zero balancing will differ from zero, though there was no change in load. This is likely to happen under the conditions, when zero balancing procedures take longer than the actual measurements and when small strain gages are excited with high bridge supply voltages. These deviations can become especially large if the measuring points are selected manually and excited for a longer time period.

## 2. SIGNAL SHIFTS OF STRAIN GAGES INDUCED BY HEAT EFFECTS

When a strain gage is to be measured with the help of a scanning unit, the strain gage has to be energized in a first step. When the excitation voltage is applied to a strain gage, the temperature of the strain gage starts to rise, until the flow of electrical excitation power is balanced by the absorption of the heat power flow into the specimen and to a much smaller part into the tap wires and the surrounding air. The amplitude and the time function of the heat-up period depend on several parameters, as excitation voltage, size and resistance of the strain gage, the adhesive and the thickness of the glue line, the material and sometimes also on the mass of the specimen. This paper covers only test results of strain gages adhered to massive ferritic steel and aluminium specimen, where the temperature increase of the specimens could be neglected, because of their mass. Temperature dependent changes of the specific strain gage grid resistance occur in the applied gage owing to the linear thermal expansion coefficients of the grid and specimen materials and the thermal coefficient of the specific electrical resistance. These resistance changes pretend mechanical strain in the specimen.

The temperature coefficient  $\alpha_a$  of an applied strain gage can be calculated [1] according to equation (1):

$$\alpha_a = \alpha_s - (\alpha_g - \alpha_r/k) \quad \text{in } \text{m m}^{-1} \text{ K}^{-1} \quad [1]$$

$\alpha_s$  = thermal expansion coefficient of the specimen

$\alpha_g$  = thermal expansion coefficient of the strain gage grid material  
(15

ppm with Constantan)

$\alpha_r$  = thermal coefficient of the specific electrical resistance of the strain gage grid material

k = gage factor

In order to keep apparent strain due to temperature changes as small as possible, the strain gages are matched during the production to a certain linear thermal expansion coefficient, e.g. matched to steel, aluminium, quartz, or plastics. This is done by changing the thermal coefficient of the specific electrical resistance. The resulting temperature coefficient of the applied gage, which is obtained after the application of the matched strain gage to the appropriate measurement object, is

approximately zero ( $\alpha_a = 0$ ).

In this case, according to equation (1) the strain of the specimen caused by temperature change is compensated for the apparent strain of the applied strain gage. This leads to equation (2):

$$\alpha_s = \alpha_g - \alpha_r/k \quad [2]$$

In cases where strain gages heat up due to the energizing voltage while the temperature of the specimens remains approximately constant because of their good thermal conductivity the length of the specimens remains unchanged while due to heating the grids of the strain gages would expand if they had not been fixed to the specimens and that is the reason why the strain gages show negative apparent strain. This apparent strain can be calculated according to equation (3):

$$\epsilon_a = (\alpha_g - \alpha_r/k) * \Delta T \quad [3]$$

$\Delta T$  = difference between the temperature of the strain gage grid and the temperature of the specimen

In cases when strain gages and specimens are thermally matched, equations (2) and (3) lead to equation (4):

$$\epsilon_a = \alpha_s * \Delta T \quad [4]$$

Vice versa, the difference  $\Delta T$  between the temperature of the strain gage grid and the temperature of the specimen material is easily obtained when the apparent strain of the applied strain gage can be measured and the values of  $\alpha_g$ ,  $\alpha_r$  and  $k$  are known. Rearranging equation (3) leads to:

$$\Delta T = \epsilon_a / (\alpha_g - \alpha_r/k) \quad [5]$$

In cases when the strain gages are thermally matched to the thermal expansion coefficient of the specimen the difference  $\Delta T$  of the temperatures is even easier to obtain by rearranging equation (4):

$$\Delta T = \epsilon_a / \alpha_s \quad [6]$$

Equations (3) and (4) show an interesting piece of information. If the applied strain gages are matched to materials with  $\alpha_s = 0$ , heat effects would not result in any apparent strain, even, if the thermal expansion coefficient of the specimen is quite different from zero. Fig. 1 shows the apparent strain  $\epsilon_a$  as a function of time after switching on the energizing voltage. The strain gage is a foil type 3/120 LY11 (see also table 1; No.4...6) matched to, and adhered on, a block of ferritic steel. The measured curves fit pretty well into the expected exponential behaviour.

$$\epsilon_a = \epsilon_{a0} * (1 - \exp(-t/\tau)) \quad [7]$$

$\epsilon_{a0}$  = apparent strain after heat-up has stabilized

$\tau$  = Time constant of the measured curve immediately after switching on the excitation voltage

The theoretical approximation of the measured curves can be improved a bit, if two exponential functions with different time constants and different amplitudes are superimposed. The parameters are shown in equation (8):

$$\varepsilon_a = \varepsilon_{a0} * (0.8 * (1 - \exp(-6/7 * t / \tau)) + 0.2 * (1 - \exp(-3 * t / \tau))) \quad (8)$$

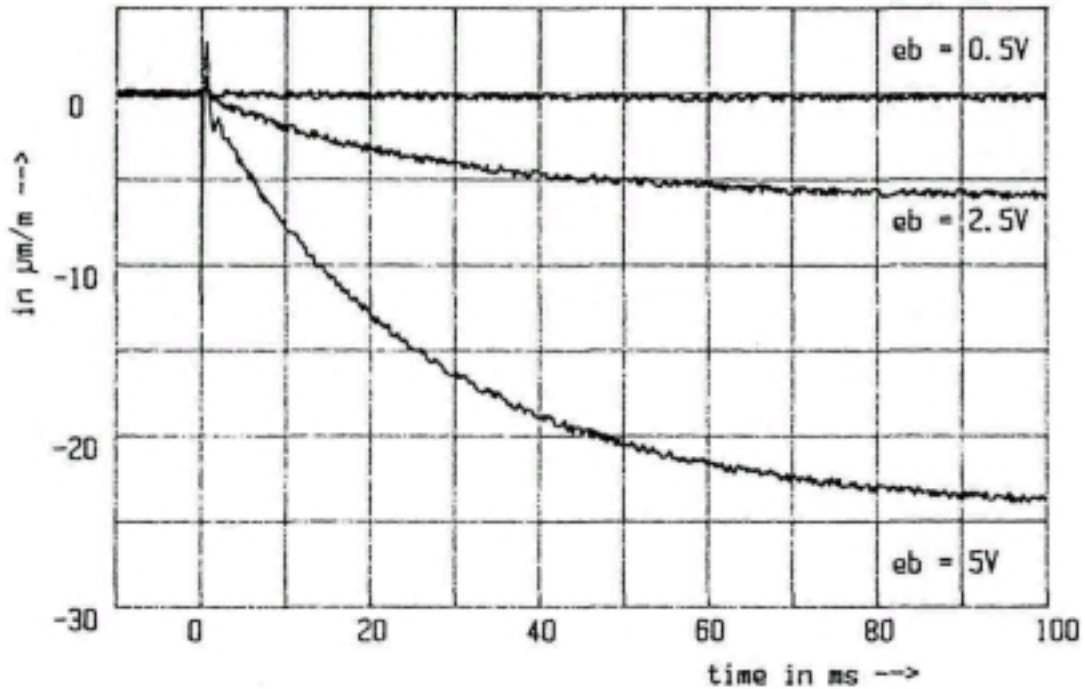


FIGURE 1. Apparent strain aa of an applied strain gage type 3/120 LY11 when bridge supply voltage is switched on

Table 1 gives a selection of results with several measuring parameters varied. Obviously, the amplitude of the apparent strain is proportional to the square of the bridge supply voltage. The smaller the active grid area, the bigger the apparent strain induced by heat effects, but also the shorter the time constants. The time constant of a heat-up period depends also on the type of adhesive, the thickness of the glue-line and the material of the specimen. The hot curing adhesive EP250 provides better thermal conductivity than the cold curing adhesives Z70 and X60. That's why the time constants of the tests of No.7 to No.12 are especially short and the apparent strains are pretty low. With Z70, a one component adhesive, thinner gluelines can be achieved than with X60. That is the reason why the tests with Z70 show shorter time constants and lower apparent strain amplitudes than the tests with X60, a two component adhesive. But it has to be mentioned that the results depend also strongly on how carefully the application was made. The given values in table 1 are average test results

of several carefully applied strain gages. The thermal conductivity of the specimen has also some influence on the heat effects. This becomes obvious if test No. 7 is compared with test No.10. The temperature difference  $\Delta T$  raises to 1.4 K, if strain gages are adhered with EP250 on steel specimens compared to only 1.1 K if adhered under the same conditions on aluminium specimens. A possible explanation could be that the

TABLE 1. HEAT UP EFFECT DEPENDENCES ON VARIOUS EXPERIMENTAL CONDITIONS

No.	experimental conditions					experimental results				
	strain gage type	grid length [mm]	specimen material	adhesive	$e_b$ [Vrms]	$\epsilon_{00}$ [ $\mu\text{m}/\text{m}$ ]	$\Delta T$ [K]	$\tau$ [ms]	settling time [ms]	
									$\pm 10\mu\text{m}/\text{m}$	$\pm 1\mu\text{m}/\text{m}$
1	3/120 LY 11 matched to steel with $\pm 11 \cdot 10^{-4}$ K [6.1ppm/°F]	3	steel S137	X60	5	-35	3.2	30	35	150
2					2.5	-9	0.8	0	75	
3					0.5	< -1	0.03	0	0	
4				270	5	-25	2.2	20	15	60
5					2.5	-6	0.5	0	35	
6					0.5	< -1	0.02	0	0	
7				EP250	5	-15	1.4	15	5	40
8					2.5	-4	0.35	0	20	
9					0.5	< -1	< 0.02	0	0	
10	3/120 LY 13 matched to aluminium with $\pm 23 \cdot 10^{-6}$ K [12.7ppm/°F]	3	AL	EP250	5	-26	1.1	12	10	40
11					2.5	-6.5	0.3	0	25	
12					0.5	< -1	< 0.02	0	0	
13	1/120 KY 15 strain gage chain matched to steel with $\pm 11 \cdot 10^{-4}$ K [6.1ppm/°F]	0.6	S137	Z70	5 <sup>1)</sup>	-160	14.5	8	25	100 <sup>2)</sup>
14					2.5 <sup>1)</sup>	-40	3.6	12	30	
15					0.5	-1.5	0.15	0	3	
16	10/120 LY 11 matched to steel with $\pm 11 \cdot 10^{-4}$ K [6.1ppm/°F]	10	S137	Z70	5	-3	0.25	50	0	50
17					2.5	< -1	0.06	0	0	
18					0.5	= 0	< 0.01	0	0	

1) Only  $e_b \pm 1.5V$  allowed  
2) Owing to creep effects because of overheating

area of the steel specimen directly below the strain gage grid may have heated up for about 0.4 K, whereas the area of the aluminium specimen may have heated up for only 0.1 K due to the thermal conductivity of aluminium, four times superior to that of steel.

All test results show surprisingly short time constants. It can be stated, that 100 ms after powering the strain gages, the remaining error is lower than 1  $\mu\text{m}/\text{m}$  in almost every case. When supplying the bridge with 0.5 V, the apparent strains generated by heat effects are near or far below 1  $\mu\text{m}/\text{m}$ .

### 3. HEAT EFFECTS AND COUNTERMEASURES

Though the heat effects settle in about 100 ms, they cannot be ignored when measuring rates rise to tens or even hundreds of measurements per second. A measurement taken at high speed immediately after switching on the excitation voltage, may differ from continuously taken measurements up to

apparent strains of  $E_{ao}$  in table 1. That is why fast measurements taken immediately after zero balancing may differ considerably from zero if zero balancing of the measuring points is done manually or in a longer automatic balancing procedure. If a group of strain gages join the same compensation strain gage, the measurements of the different measuring points may differ from one another though they have been zero balanced in a correct short measuring circle just a short time before and no mechanical stress has been applied in the mean time. The source for these deviations can be traced to heat-up effects of the compensation strain gage. When the first strain gage of the group is being switched to the excitation voltage, the dummy gage or compensation gage will also be switched to the excitation voltage for the first time and therefore will show about the same heat-up effects as the measured strain gage, whereas the heat-up effects of the compensation strain gage settle during the following measurements. That is why the heat-up effects of the strain gage switched on first in a group may show nearly no apparent strains, whereas the others show increasing apparent strain amplitudes.

Now, what can be done to avoid measuring errors due to these heat effects? Different methods may be adopted. Application of one of the following hints may be sufficient. Here are some suggestions:

- ◆ Use strain gages with thermal coefficients  $\alpha_a = 0$  and try to achieve temperature compensation with the help of an unstressed compensation gage close to the common group of strain gages
- ◆ Use a separate compensation gage for each measured strain gage
- ◆ Choose bridge supply voltages of  $\leq 0.5$  V
- ◆ Delay each measurement for about  $\geq 50$  ms until heating has settled
- ◆ Perform zero balancing and measurements in equal time periods
- ◆ If a measuring point is to be displayed continuously the energizing voltage should be pulsed
- ◆ Supply the strain gages with carrier frequency to suppress thermo coupled voltages generated by heat effects

Fig. 2 shows a scanning unit of the type UPM60 which provides all of the above mentioned features. The strain gages can be powered with 225 Hz carrier frequency bridge supply voltages of 5 V or 0.5 V. Measurements can be taken up to speeds of 100 measuring points per second and the zero balancing time is always equal to the measuring time. When selecting the measuring points manually, the UPM60 powers the strain gages only for about 40 ms every 500 ms interval time to reduce heating.

#### 4. UNIVERSALLY APPLICABLE MULTIPOINT MEASURING UNIT

Apart from the heat-up effects, many other error sources exist if measuring strain gages, especially if they have to be measured in quarter bridge circuits. The biggest error sources may be voltage drops across the measuring leads and switching elements, because strain gage signals are very



FIGURE 2. Scanning unit equipped with dc and carrier frequency amplifiers to provide highest precision with various transducer types

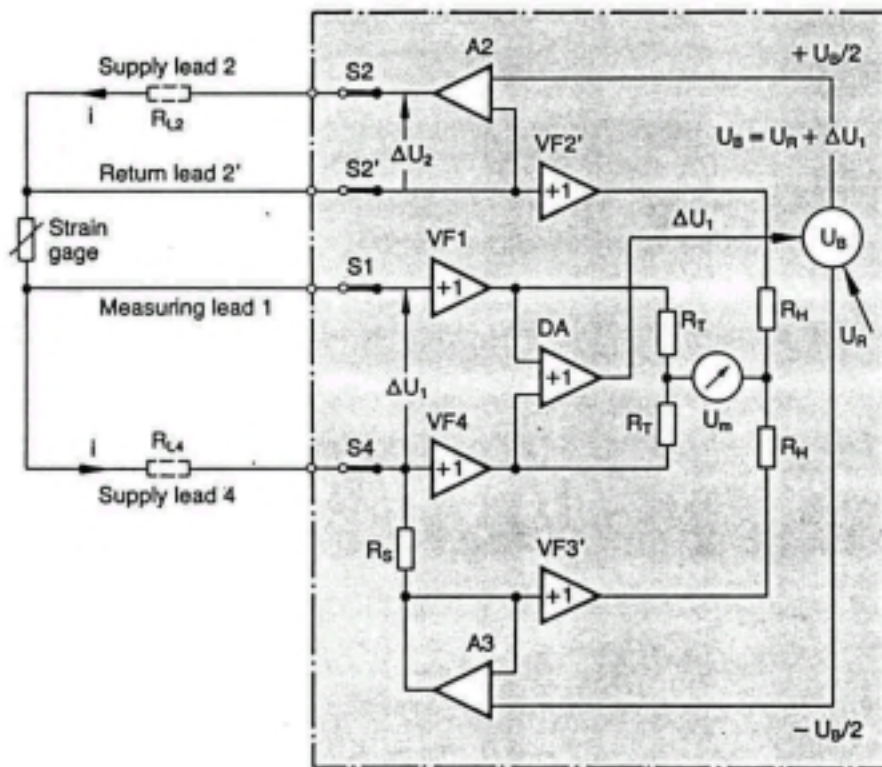


FIGURE 3. New bridge circuit reduces zero and sensitivity errors significantly with internal feedback circuits which correct for voltage drops across the leads and switches

low and voltage drops may exceed equivalent strain gage measuring signals of 100,000  $\mu\text{m}/\text{m}$ . The UPM 60 uses a patented, highly sophisticated intermediate circuitry [2]. Errors due to voltage drops are avoided almost completely. Fig. 3 shows a simplified schematic diagram of the bridge circuit of the UPM 60.

Feed back techniques have been adopted which allow to choose reliable semiconductor switches (FET), though they have got higher "switch on" resistances, compared with mechanical contacts. This circuit provides the possibility of connecting strain gages in quarter bridge circuits which can be located up to 500 ... 1000 m apart from the UPM60.

But of course, the UPM 60 is not limited to measurements with strain gages in quarter bridge circuits only. It is equipped with suitable selector modules for connecting strain gages in quarter, half and full bridge, inductive transducers as displacement transducers, thermocouples, Pt100 resistance thermometers, resistance transducers and any voltage and current sources. In order to meet these demands the UPM 60 is equipped with three different types of amplifiers:

a dc-amplifier mainly for the purpose of measuring thermocouples and voltage or current sources or for high speed strain gage measurements,

a 225 Hz carrier frequency amplifier for high precision measurements with strain gages and resistance transducers, a 5 kHz carrier frequency amplifier to provide the possibility to measure inductive transducers.

The UPM 60 can connect and measure up to 60 measuring points with mixed transducer types to meet the modern test requirements of measuring stresses, forces, displacements and temperatures simultaneously.

The UPM60 provides many data processing functions and is equipped, as standard, with RS 232-C and IEEE 488 interfaces to allow remote control and additional online data processing with the help of an external computer.

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