Welcome to the webinar
‘How to calculate a strain gauge's excitation voltage’

The webinar starts at 10 a.m. CET.
Speaker

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  HBM Test and Measurement
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How to calculate a strain gauge's excitation voltage

Maximum permissible effective bridge excitation voltage of a strain gauge:
How is it calculated, and what has to be taken into account in actual applications?
Agenda

1. Theory
   - Strain gauge as heating element
   - Influencing factors for heating
   - Heat flow model

2. Calculating maximum permissible bridge excitation voltage
   - From the heat flow model to $U_{\text{max}}$
   - Thermal conductivity of different materials

3. Specifics and use in practice

4. Additional information and Q&A
Agenda

1. **Theory**
   - Strain gauge as heating element
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Strain gauge as heating element

Applied voltage results in a loss of power \( P = \frac{U^2}{R} \)

A strain gauge is a electrical resistor

Heat (power) must be discharged:

- Through the carrier (thermal isolation)
- Assimilation by the measurement body
- Discharge via air is quite small

\[ U_{\text{max}} = \sqrt{P \cdot R} \]
Measurement errors when strain gauge heats-up

**Measurement errors:**

- Apparent strain through thermal expansion  
  → zero drift

- Deterioration of the strain gauge's self-temperature-compensation  
  *(result of differences in thermal expansion between the measuring body & strain gauge)*  
  → zero drift

- Potential exceeding of temperature limits (e.g. of the adhesive)  
  *(through additional heating when measure on high temperature range already)*

**Reasonable limits to guarantee minimum measurement error**

- An increase of 5°C will be tolerated  
  *(delta between measurement body and strain gauge)*

- Results in an error less 1 μm/m on room temperature  
  *(worst case less than 10 μm/m on higher temperature level)*
The following factors have a significant impact on heating (and thus on the maximum permissible bridge excitation voltage $U_{\text{max}}$)

- Strain gauge resistance $R$
  (higher resistance produces lower heating)

- Strain gauge grid area $A$
  (larger area allows better heat dissipation)

- Thermal conductivity $\lambda$ of the measuring body
  (describes the 'efficiency' of heat dissipation)

- Special features
  (for example the strain gauge design [stacked grids])
Assumptions:
- Strain gauge bonded on a measurement body with infinite thermal capacity C
- Temperature gradient $\Delta T/d$ develops close to the strain gauge (temperature difference between the strain gauge and the measuring body)
- Gradient is independent of the grid area and strain gauge resistance → measure in fault analysis

Heat flow model #1

Empirical studies:
Limit for the measurement error is generally complied with at a temperature gradient of $\Delta T/d = 0.75 \, ^\circ C/mm$
The dissipated heat energy $\dot{Q}$ results from

- Strain gauge grid area $A$ (length $\cdot$ width)
- Measuring body's specific thermal conductivity $\lambda$
- Temperature gradient $\Delta T/d$ (constant factor of 0.75 °C/mm)

$$\dot{Q} = A \cdot \lambda \cdot \frac{\Delta T}{d}$$

In stationary mode, a balance is created between the electric power $P$ and the heat energy $\dot{Q}$ dissipated through the carrier to the measuring body (temperature in strain gauge does not change any more)

$$P = \dot{Q}$$
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From heat flow model to $U_{\text{max}}$

**Heat flow model:**

$$Q = A \cdot \lambda \cdot \frac{\Delta T}{d} \quad P = \dot{Q} \quad U_{\text{max}} = \sqrt{P \cdot R}$$

**Maximum permissible bridge excitation voltage**

$$U_{\text{max}} = \sqrt{R \cdot A \cdot \lambda \cdot \frac{\Delta T}{d}}$$

- **Resistance $R$** Strain gauge property [Ω]
- **Measuring grid area $A$** The measuring grid area [mm²] (length • width)
- **Thermal conductivity $\lambda$** Property of the measuring body material [W/m•K] (see table on next slide)
- **Temperature gradient $\Delta T/d$** Empirical value of 0.75 °C/mm (minimizes error to ≤ 1µm/m @RT)
## Thermal conductivity of different materials

<table>
<thead>
<tr>
<th>Material</th>
<th>Thermal conductivity $\lambda$ [$W/m\cdot K$]</th>
<th>HBM identifier</th>
<th>Correction factor for steel</th>
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<tr>
<td>Ferritic steel</td>
<td>50</td>
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<td>Aluminum</td>
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<td>3</td>
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<td>Austenitic steel</td>
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<td>0.12</td>
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<td>Titanium/gray cast iron</td>
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<td>7</td>
<td>0.66</td>
</tr>
<tr>
<td>Plastic</td>
<td>&lt; 0.05</td>
<td>8</td>
<td>0.03</td>
</tr>
<tr>
<td>Molybdenum</td>
<td>136</td>
<td>9</td>
<td>1.65</td>
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</tbody>
</table>

**Tip:**

Use right column as correction factor when only the maximum excitation voltage for strain gauges matched to steel is known, however, the strain gauge is installed on another material.

Correction factor $= \sqrt{\frac{\lambda_{\text{Material}}}{\lambda_{\text{Steel}}}}$
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Specifics of the maximum bridge excitation voltage #1

**Carrier frequency**
The effective value of the maximum bridge excitation voltage is reduced by a factor of 0.7 \((1/\sqrt{2})\) for sinusoidal carrier frequency.

→ *Carrier frequency excitation is a better choice, since it heats up the strain gauge to a lesser degree compared to DC voltage*

**Stacked rosettes**
Individual measuring grids are stacked one on top of the other. Upper measuring grids can dissipate heat to the measuring body to a lesser degree than the lower ones. The maximum permissible bridge excitation voltage therefore needs to be reduced by a factor of 0.7 \((1/\sqrt{2})\) with a T-rosette with two stacked measuring grids and by a factor of 0.6 \((1/\sqrt{3})\) with a rosette with three measuring grids.

**Weldable strain gauges**
Heat flow through the spot welds is reduced, which results in a lower maximum permissible effective bridge excitation voltage.
Specifying the maximum bridge excitation voltage #2

**Encapsulated strain gauges**
The formula given applies for encapsulated strain gauges as well
*(Only heat dissipated via measuring body - heat dissipation to the ambient air [convection heat transfer] is neglected)*

**Laminated strain gauges**
Strain gauges that can be laminated are typically used in environments with poor thermal conductivity (e.g. composites)
→ Choose lowest possible bridge excitation voltage

**Extreme conditions**
If heating of the strain gauge needs to be ruled out entirely *(e.g. measuring in high-quality vacuum or extremely low temperatures [~0K]*)
→ Use optical strain gauges (fiber bragg grating)
Slightly exceeding $U_{\text{max}}$ does not damage the strain gauge

- Measurement error primarily consisting of a zero offset
  (with dynamic measurements, even that is irrelevant)

- Strain gauge's maximum effective excitation voltage is specified on the data sheet of the strain gauge packaging

- If another material is used that specified (different thermal conductivity $\lambda$) use the table on slide 12 to find the correction factor

- We are talking about a maximum excitation voltage
  \( \Rightarrow \text{The value used in the amplifier can be significantly lower} \)

- Heat dissipation increases quadratically with the excitation voltage
  \( \Rightarrow \text{Excitation voltage below results in a significant minimization of the error} \)

- For carrier frequency amplifiers use a factor of 0.7 (effective voltage value)
  \( \text{(Safety margin with CF)} \)

- Critical are measurements on materials with very poor thermal conductivity
  \( \Rightarrow \text{Smallest possible excitation voltage and highest possible resistance for plastic} \)

- Rule of thumb: use excitation voltage of 2.5 V
  \( \text{(measurement on steel and a strain gauge with 1.5 mm grid length and 350}\Omega\text{ resistance)} \)
  \( \Rightarrow \text{Far from the maximum effective excitation voltage - no measurement error} \)
A strain gauge is an electrical resistor with a loss of power
\( P = U^2 / R \)

Heat must be discharged via test object
\( \rightarrow \text{Assimilation} \)

Measurement error can be seen as a zero drift
\( \rightarrow \leq 1 \mu m/m \text{ for room temperature} \) (\( \leq 10 \mu m/m \text{ worst case} \))

\( U_{\text{max}} \) can be calculated with given parameters:

\[
U_{\text{max}} = \sqrt{R \cdot A \cdot \lambda \cdot \frac{\Delta T}{d}}
\]

- Resistance \( R \) Strain gauge property [\( \Omega \)]
- Measuring grid area \( A \) The measuring grid area [mm\(^2\)]
- Thermal conductivity \( \lambda \) Property measuring body material [W/m\( \cdot \)K]
- Temperature gradient \( \Delta T/d \) Empirical value of 0.75 °C/mm

Heat dissipation increases quadratically
\( \rightarrow \text{Stay below max. value and/or use carrier frequency} \)

On critical materials (e.g. composite/plastic) use lowest voltage and/or bigger strain gauge
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→ www.hbm.com/strain

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<td>Structural health monitoring in towers and foundations of wind turbines</td>
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<td>Apr 30, 2014</td>
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Any questions?

- Please contact our Support Team for further questions.
  We look forward to your email: info@de.hbm.com

- Or email the speaker directly: jens.boersch@hbm.com
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