Temperature Induced Drift in Mechanical Load Measurements on Wind Turbines

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In the context of increasing size of the turbines and the associated financial risk of a systematic component failure high accuracy load measurements are needed in the validation process for computational wind turbine models. Such validation is indispensable for rating a specific design as well as for performance verification of the modelling tool itself.
New measurement systems suggest high measurement resolution and attractive accuracy. On the other hand, in field strain gage measurements may still suffer from considerable temperature drift, at times masking the sought after statistical characteristics of the variable under investigation. Such rather slow variations in the load variables are considered uncritical for fatigue life analysis but make ultimate measured load analysis somewhat vague. Due to the specific properties of the GRP (glass fiber reinforced plastics) material, a particular sensitivity to that phenomenon can be observed in load measurements on wind turbine rotor blades.

Physical influence of temperature on wind turbine loads

The air density (ρ) has a linear influence on the available power of a wind turbine and thus, as long as there is no power control like pitch action, also on the loads (ρ ~ M). In power performance measurements this effect is considered, but in load measurements it is neglected. The air density is calculated by using the air pressure, temperature and gas constant.

Diagram 1 shows the load change as a function of the air pressure (upper) and the temperature (inferior). The bending moment decreases approximately –0.33% per 1° temperature change.

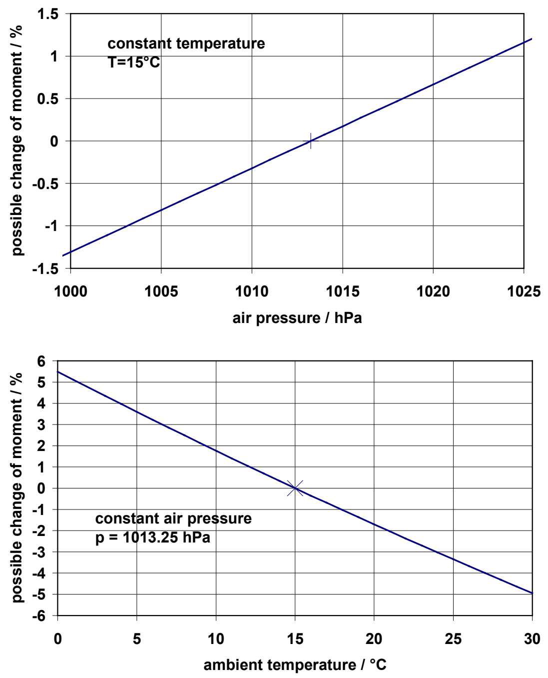

Diagram 1: Change of rotor blade bending moment as a function of air pressure (upper) and temperature (inferior) starting from standard air pressure 1013.25 hPa and standard temperature 15°, assuming no power control action.

In diagram 2 the observed temperature drift of 12 rotor blade measurements gives often higher absolute values.

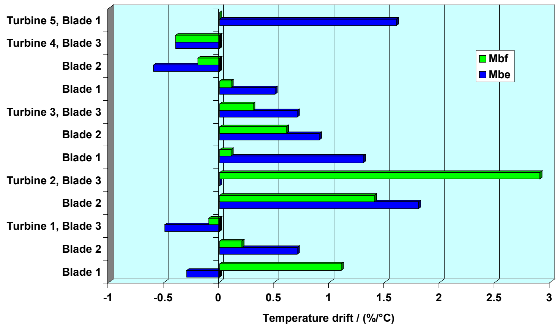

Diagram 2: Temperature drift of edgewise Mbe and flatwise Mbf bending moment (between start up and rated wind speed) related to the dead mass calibration cycle.

This paper describes the governing reasons for the observed temperature drifts and discusses counteractive measures:

- Temperature compensated strain gage bridge configurations
- Temperature coefficient at glass fiber reinforced plastic
- Temperature dependency of electrical wires
- Temperature drift of measurement device
- Compensation of temperature drifts by using multi regression analyses

Temperature compensated strain gage bridge configuration

The optimisation of the strain gage set-up allows for the best reduction of temperature drift errors. As a good practice temperature compensated bridge configurations are used to compensate the signal created by thermal expansion of homogeneous materials. Diagram 3 left shows the tension strain in force direction and compressive strain in the perpendicular direction. The strains are measured by a Wheatstone bridge according to the following equation.

$^{Ua}/_{Ub}={}^{k}/_{4}(\varepsilon_x-\varepsilon_y+\varepsilon_x-\varepsilon_y)$

Diagram 3 (right) shows the temperature expansion strains in all directions of a homogeneous material like steel. The thermal strain induced resistance increase is compensated by the Wheatstone bridge, see following equation.

$^{Ua}/_{Ub}={}^{k}/_{4}((\varepsilon_x+\alpha_x)-(\varepsilon_y+\alpha_y)+(\varepsilon_x+\alpha_x)-(\varepsilon_y+\alpha_y))$
for $\alpha_x=\alpha_y$
$^{Ua}/_{Ub}={}^{k}/_{4}(\varepsilon_x-\varepsilon_y+\varepsilon_x-\varepsilon_y)$

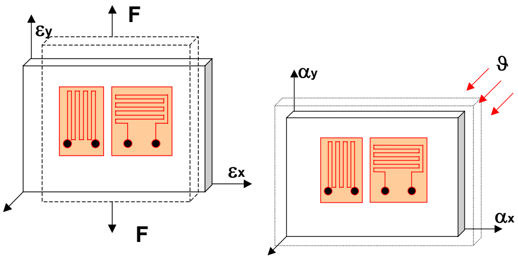

Diagram 3: Strain gages bonded to a homogeneous material like steel under an axial load (left) and during a temperature change (right).

Temperature coefficients of glass fiber reinforced plastic

By looking into the micro mechanics plastic has a higher extension coefficient than glass. The temperature coefficient of glass fiber reinforced plastic is depending on the fiber direction and the glass content of the plastic. In one product example the extension coefficient in glass fiber direction is $\alpha_{II} = 7\ ^{\mu\ strain}/K$ and in the perpendicular direction $\alpha_{\perp} = 27\ ^{\mu\ strain}/K$ for a fiber content of 60%, see diagram 4.

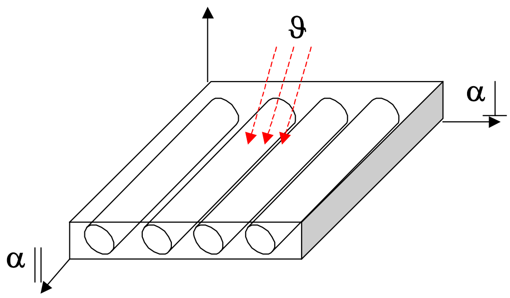

Diagram 4: The temperature coefficient of fiber reinforced plastic is depending on the fiber direction and the fiber content of the plastic.

In rotor blades different types of textures are used to take bending or torsion moments. At the leading or trailing edge side of rotor blades torsion is taken by a cross meshed texture as shown in the left side of diagram 5. At the suction or pressure side of a rotor blade unidirectional textures are used to take the high bending moments, see middle of diagram 5. As a surface cover textures as shown on the right side of diagram 5 are used. For strain gage measurements only the surface layer is relevant.

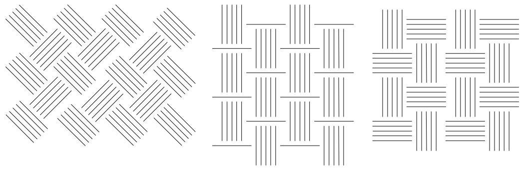

Diagram 5: Different type of textures of fiber rein force plastic.

Du to the coated surface the texture of the fiber can not be identified before bonding a strain gage. In the extreme example of diagram 6 one strain gage is bonded to fiber direction and the other is bonded to perpendicular fiber direction only. It is assumed that the surface can extend freely. The right strain gage will see a higher temperature extension than the left strain gage, see right side of diagram 6. The different thermal strain is measured in the Wheatstone bridge. In this hypothetical temperature drift example the bridge output is in the range of $(\alpha_{\perp} - \alpha_{II})/2 = 10\ ^{\mu\ strain}/K$. By comparing the temperature extension to external calibration values of rotor blades, this temperature drift reaches values of up to 2%/C° and is not negligible.

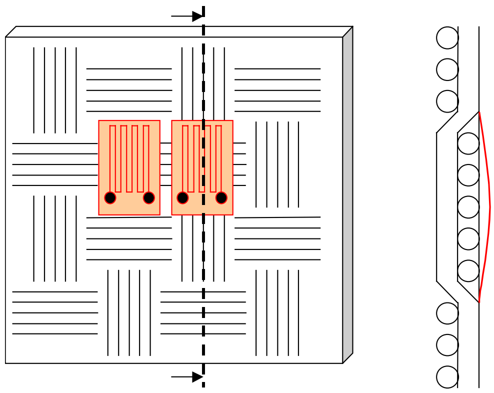

Diagram 6: Local temperature surface extension influence strain gage unsymmetrically.

Temperature dependency of electrical wires

The electrical resistance of the internal Wheatstone bridge wiring is influenced by temperature effects, see Diagram 7.

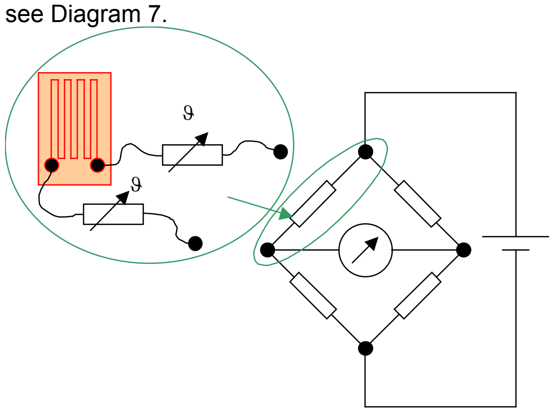

Diagram 7: Change of sensitivity due to temperature dependency of electrical resistance of the connection wires inside Wheatstone bridge circuit. Different temperatures change the bridge balance.

To reduce this effect this cable has to be of

- large cross section,
- short length and
- less effect when using high resistance strain gages

As an example (350 Ohm strain gage, 0.14 mm² copper cable) a temperature drift of 0.07 %/°C per meter cable between strain gage and Wheatstone connection point will occur compared to the measured value. This kind of temperature drift will cause a change of sensitivity. In this example it is assumed that all cables see the same temperature change.
In case there is a temperature difference between both sides of the bridge an unbalance results and will give an offset error. In the given example there will be a temperature drift of 0.2 %/°C per meter cable at an assumed unbalance of 1 mV/V. If the bridge is balanced the different cable heating results in a drift of 1.4 µV/V / °Cm.

This temperature drift results only from the connection wires. The strain gages also measure the thermal expansion of the tested materials themselves which have also temperature dependencies. Self-temperature compensated strain gages tuned to the measured material are able to compensate the expansion due to the material temperature coefficient. But they still have non linear offset error and gage factor dependencies. The offset error is usually given as a function of the temperature. In one example (steel 1018) the offset error was below 4 $^{\mu\,strain}$/K and the change of gage factor was given by 0.012%/K for the temperature range 0 to 100°C. These values include the temperature coefficient of the steel. By using other materials than the strain gages are tuned for, these values are not valid.
If all strain gages are of the same type in a fore strain gage bridge the most of the offset temperature error will be compensated.
Using appropriate strain gage resistance helps to reduce supply induced heating of the strain gages when bonded to glass fiber reinforced plastic surfaces that do not allow for easy heat transfer.

The supply cables of the Wheatstone bridge are also influenced by temperature. This effect can be cancelled by using a standard 6 wire bridge connection as shown in diagram 8. The voltage unbalancing will be measured with high resistance directly at the bridge connection. The temperature indicated change of cable resistance is negligible due to the high resistance of the measurement device.

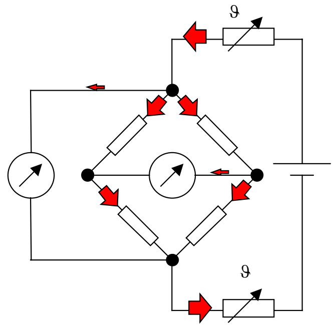

Diagram 8: Six wire bridge connections measure the voltage relation between the two arms of a Wheatstone bridge without influence of bridge supply cable.

Temperature dependency of the measurement device

Measurement system manufacturers give information about temperature drifts of their devices. In the test documented here the bridge amplifier was short circuited by short wires.
Two hours after the start of the measurement the bridge output is stable, see Diagram 9. One of the three channels reaches a drift of 0.55% of the 1 mV/V measurement range. The other two drift less.

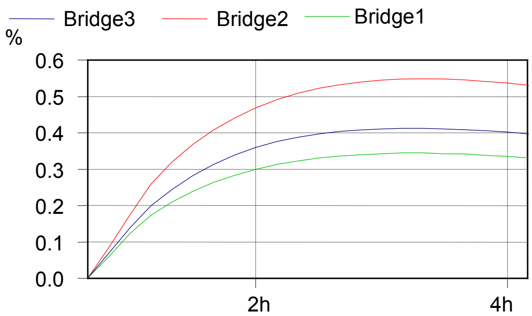

Diagram 9: Two hours after the start with short circuited bridge amplifier the measured values are stabilised.

This test was continued for three days, see diagram 10. According to this example one of the channels reaches a temperature drift of 0.9% of the measurement range by a temperature change of approximately 12°C. This temperature drift of 0.075%/°C is less than the observed temperature drift as shown in diagram 2 before. This relative temperature drift coefficient decreases when using higher measurement ranges.

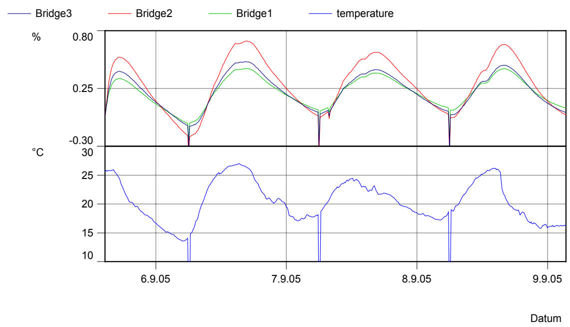

Diagram 10: Short circuited measurement output of the three bridges during three days.

Air condition may reduce environmental influences on the measurement device. Too small or not well adjusted air condition increase temperature fluctuation. Opening of the door gives fast temperature change.

Temperature drift correction by post processing of load signals

Using multiple regression analysis the temperature drift in a load signal can be quantified. For this evaluation only data were the wind turbine is operating between cut in and app. rated wind speed is used. For this evaluation it must be sure that the temperature is independent from the wind speed. Such quantification gives rise to the possibility to normalize the complete measurement campaign to the overall mean temperature. The evaluated temperature coefficient include the change from temperature influenced air density also.
Diagram 11 shows one example of 10 minute mean blade edgewise bending before and after temperature correction. The measurement range was approximately 10 times higher than the maximum mean value, because of the dominating periodic gravity cycle. Before temperature correction the turbine characteristic was hidden in a general blur. After normalising two operation modes are discernible.

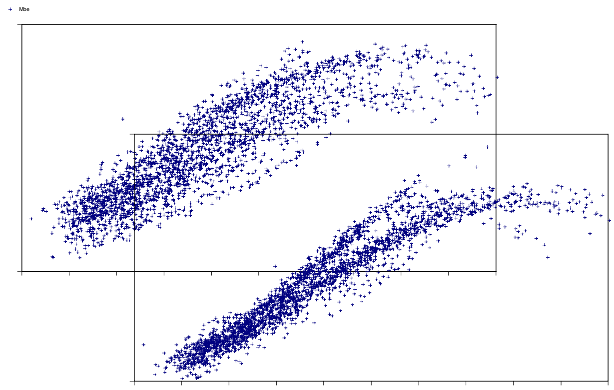

Diagram 11: Mean edge wise bending moment before and after normalising by using multi-regressions analyses.

Conclusions

In the following table different reasons for temperature drifts are listed, together with the assumed temperature drifts. The major reason at rotor blades can be found in the surface problems of the glass fiber reinforced plastic. The influence of the cable can be easily reduced by increasing the cross section. Post processing helps to correct this distortion. If requested the well known physical influence out of the air density can be removed from the overall found temperature coefficient.

Causes	**Temperature Drift**
Physical, change of air density	0.33 %/°C
Homogeneous material in a temperature compensated bridge	0 %/°C
Surface of glass fiber reinforced plastic (hypothetical example)	2 %/°C
Uniform temperature change inside the bridge	0.07 %/(°C m) 0.28 %/°C for 4m cable
Uneven temperature change inside the bridge	0.2 %/(°C m) 0.8 %/°C for 4m cable
Temperature change at strain gages	0.012 %/°C change of gage factor
Supply cable of bridge by using 6 wire application	0 %/°C
Measurement system alone (example)	0.075 %/°C