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Hardware Redundancy for Sensor Degradation Detection in SHM Systems using Strain Gauge Measurements

Jan-Hauke Bartels[a], **Steffen Marx**[a]

[a] TU Dresden, Institute of Concrete Structures, Helmholtzstr. 10, Dresden
E-mail: jan-hauke.bartels@tu-dresden.de

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1 Introduction

The use of continuous structural health monitoring (SHM) systems has become increasingly important in recent years for assessing the condition of infrastructures such as offshore wind turbines (OWTs) [1]. The method provides a continuous assessment and is a valuable complement to conventional on-site inspections and as-built data analysis [2–5]. In particular, strain-based measurement using strain gauges (SGs) is important because changes in the condition of a structure are primarily indicated by relative displacements of its components [6–8]. These sensors can be used, for example, to monitor the local damage-sensitive areas of the structure, such as, e.g., tower structure joints. At the same time, in view of the increasing digitalisation, the digital twin is being researched in the construction industry [9]. The digital twin is essentially based on linking real subcomponents of the building with digital representatives and must represent the real building as accurately as possible [10] The information required for this must be obtained through monitoring systems that ensure a lifelong link between the real and virtual systems. The problem is that for large structures the changes in state due to ageing are very small [11]. However, the measurement system is also subject to initial measurement uncertainties, so that it is often not possible to distinguish between measurement errors and changes in the condition of the structure [12]. In addition, the behaviour of the measurement system changes with time because it is not the structure that ages, but the measurement system itself. Therefore, the aim of this work is to determine how to distinguish between sensor degradation and building degradation. A correlation analysis should make it possible to distinguish between both.

2 Test setup and simulated aging effects

To detect sensor degradation, this paper uses the sensor type Strain Gauge (SG), which is often used in structural monitoring. The advantage of using SGs is that the individual components of the measurement chain can be assembled according to individual needs. In this context, this means applying partial SGs to the specimen unprotected from external influences. This makes it possible to visualize ageing phenomena in sensors more quickly. We decided to do this because it is not the ideal configuration of the measuring points that is important, but the description of the method of sensor degradation. Otherwise, months or even years would be required to detect potential ageing phenomena in measurement systems. The test setup used is shown in Figure 1.

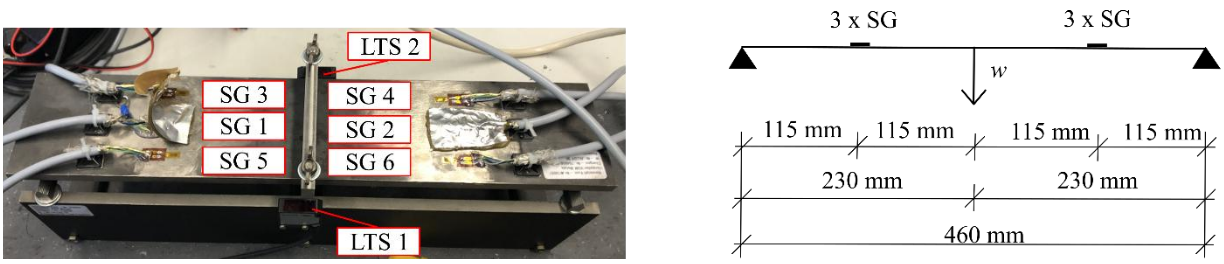

Figure 1: Test setup for the investigation of sensor degradation in strain gauges (SGs) with the use of a displacement-controlled load using laser triangulation sensor (LTS); left: realized test setup, right: idealized static system.

The left figure shows the realized test setup, the right figure visualizes the idealized static system. The test setup consists of a base plate with an upstand made of the material Alloy 36 fixed by screws. Alloy 36 is a nickel-iron alloy with low thermal expansion. The coefficient of thermal expansion is calculated to be approx. $\alpha_{T,\text{Alloy 36}} = 0.50 \cdot 10^{-6}\ 1/K$ for the used temperature range of $T = -10°\text{C} ... +50°\text{C}$ and is therefore almost smaller by a factor of 10 than for steel ($\alpha_{T,\text{Steel}} = 13.0 \cdot 10^{-6}$ 1/ K).
The sample with the SG's applied is installed in the test setup to create the static system shown in Figure 1 on the right. At each quarter position, 3 SGs are applied to the specimen to measure the strain as the specimen deforms. Using the general stress equation, this 4-point bend test can be used to compare the theoretical strain to be measured with the actual strain, and the magnitude of the measured quantity can be made plausible. For example, if we look at the left side specimen (left quarter position), we see that two of the three SGs are unprotected, while one SG is protected. In this way, we ensure an unaged measurement point that serves as a reference for detecting sensor degradation. In the next step of the experiment, the sample is loaded in a displacement-controlled manner by applying a deflection at the center of the sample field via wing nuts. The deflection is measured using high-precision laser triangulation sensors (LTS), which have a higher accuracy than the SGs and are therefore suitable for monitoring the test performance. A reference measurement is made at the beginning of the test period. Comparison measurements are then performed after each aging phase. Both measurements are performed identically by applying a deflection $w = [0.0; 0.5; 1.0; 1.5; 2.0; 2.5; 3.0]$ mm at 20 °C and 50 % RH and measuring the strain of the SGs. Thus, we have defined all controllable boundary conditions so that changes in the measured signal indicate aging.
The aging phenomena for the measurement system are simulated by varying the temperature and humidity in a climate chamber. The temperature and humidity cycles are shown in Figure 2.

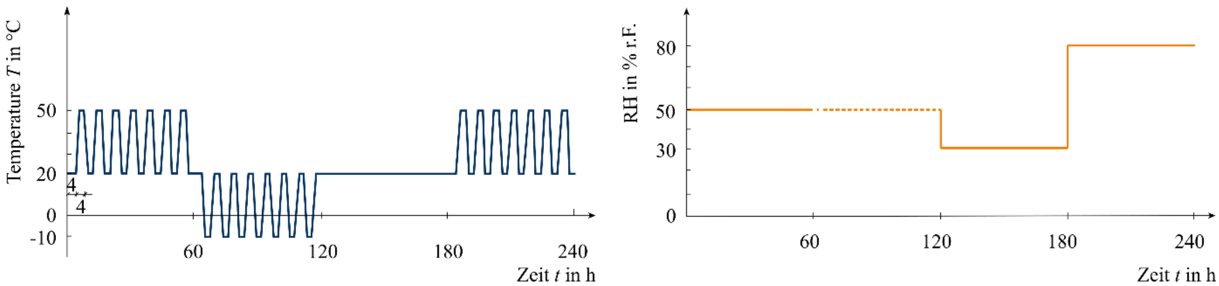

Figure 2: Control of environmental conditions inside the climate chamber, left: Control of temperature, right: Control of relative humidity (RH).

Temperatures and humidity can be divided into four phases. The actual aging process of the measurement system does not occur as a result of changes in temperature, but as a result of changes in humidity. After passing through the four aging phases, a mechanical stress measurement is performed to detect changes in the behavior of the measurement system.

3 Correlation Analysis for Sensor Degradation Detection

In this section, we analyze the acquired measurement data. For this purpose, we have plotted the raw data over time in the left sub-figure of Figure 3. In this diagram, we can see the measured values of SG 1 and SG 5 and recognize that at the beginning of the measurement (Day 0), the measured value difference is relatively small, while it increases over time. The unprotected SG 5 shows a drift in the measured values and a clear time-variant behavior, while the protected SG 1 provides reproducible measurements, i.e. does not show any drift in the measured values. In addition, the red box shows an example of how both SGs react to changing environmental conditions (temperature and humidity). Again, SG 5 shows more significant changes in the measurement signal than SG 1 due to the measurement point protection. The red dashed lines show the mechanically induced strains during the test. At these time points, the sample was deflected as described in section 2. Day 0, Day 6 and Day 23 are used for evaluation.

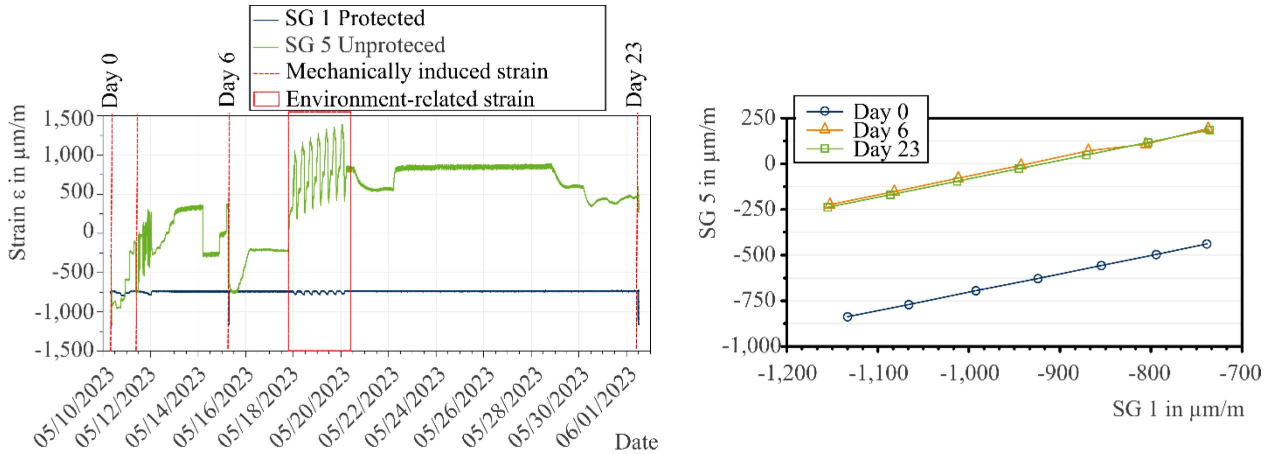

Figure 3: Darstellung der Messdaten von SG 1 und SG 5, links: Rohdaten über die Zeit, rechts: Korrelation zwischen SG 1 und SG 5

The right subfigure of Figure 3 shows the result of the correlation analysis between SG 1 and SG 5. While the blue line represents the reference of the test to day 0, the orange and green lines show a clear shift on the y-axis. With this correlation analysis it is possible to detect sensor degradation in the SHM system. Thus, it can be reliably said that there is no damage to the structure, but there is damage to the SHM system.

In order to determine which of these sensors (SG 1 or SG 5) is subject to aging in the next step, the raw data signal (Figure 3, left subfigure) can be used for qualitative evaluation. For the quantitative evaluation, the autocorrelation analysis should be performed according to the scheme in Figure 3, right subfigure. In this case, the autocorrelation between SG 1 at day 0 and SG 1 at day 6 or 23 is evaluated.

Table 1: Autocorrelation for SG 1 and SG 5

	Day 0		Day 6		Day 23	
	SG 1	SG 5	SG 1	SG 5	SG 1	SG 5
y_0 in µm/m	-738.79	-440.30	-737.34 (-0.2 %)	193.90 (+144.0 %)	-735.56 (-0.4 %)	186.06 (+142.3 %)
m	1.00	1.00	1.04 (+4.0 %)	1.02 (+2.0 %)	1.05 (+5.0 %)	1.05 (+5.0 %)
$\overline{\sigma}$ in µm/m	2.43	2.43	2.67 (+9.9 %)	5.23 (+115.2 %)	4.27 (+75.7 %)	2.47 (1.6 %)

We see that SG 1 deviates only -0.2% and -0.4% from the reference value after day 6 and day 23, respectively, while SG 5 deviates significantly from the reference value with +144% and +142%. This shows that the unprotected SG 5 is subject to sensor degradation and should be replaced in practice. The slope of the autocorrelation regression and the standard deviation hardly changed during the measurements, so they will not be discussed further in this work.

4 Conclusion and Outlook

In this paper, we have presented a redundancy approach for robust SHM systems. This approach considers hardware redundancy, i.e., a redundant number of sensors measuring the same physical quantity in close vicinity to the component to be monitored. For this purpose, we used SGs and subjected them to ageing through temperature and relative humidity cycles. At different times, we analysed the correlation between two SGs and the autocorrelation of each SG. With this study, we were able to show that the presented hardware redundancy approach provides a robust method for detecting sensor degradation. In future studies, we will perform this investigation over a longer period of time and analyse whether not only a measurement drift, but also a change in the slope of the regression coefficients or a change in the standard deviation occurs. Both are also indicators of sensor degradation.

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References

[1] Farrar, C. R.; Worden, K. (2007) *An introduction to structural health monitoring* in: Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences 365, Nr. 1851, pp. 303–315. https://doi.org/10.1098/rsta.2006.1928

[2] Pozo, F.; Tibaduiza, D. A.; Vidal, Y. (2021) *Sensors for Structural Health Monitoring and Condition Monitoring* in: Sensors (Basel, Switzerland) 21, Nr. 5, pp. 1–6. https://doi.org/10.3390/s21051558

[3] Ciang, C. C.; Lee, J.-R.; Bang, H.-J. (2008) *Structural health monitoring for a wind turbine system: a review of damage detection methods* in: Measurement Science and Technology 19, Nr. 12, p. 122001. https://doi.org/10.1088/0957-0233/19/12/122001

[4] Ou, Y. et al. (2021) *Vibration-based monitoring of a small-scale wind turbine blade under varying climate conditions. Part I: An experimental benchmark* in: Structural control & health monitoring 28, Nr. 6, e2660. https://doi.org/10.1002/stc.2660

[5] Bas, J. et al. *Strain Response of a Wind Turbine Tower as a Function of Nacelle Orientation*.

[6] Sun, Z.; Zou, Z.; Zhang, Y. (2017) *Utilization of structural health monitoring in long-span bridges: Case studies* in: Structural Control and Health Monitoring 24, H. 10, 1-12. https://doi.org/10.1002/stc.1979

[7] Yoon, H.; Shin, J.; Spencer, B. F. (2018) *Structural Displacement Measurement Using an Unmanned Aerial System* in: Computer-Aided Civil and Infrastructure Engineering 33, H. 3, S. 183–192. https://doi.org/10.1111/mice.12338

[8] Philips Adewuyi, A.; Wu, Z.; Kammrujaman Serker, N. H. (2009) *Assessment of vibration-based damage identification methods using displacement and distributed strain measurements* in: Structural Health Monitoring: An International Journal 8, H. 6, S. 443–461.

[9] Grabe, M. et al. (2020) *smartBridge Hamburg – prototypische Pilotierung eines digitalen Zwillings* in: Bautechnik 97, H. 2, S. 118–125. https://doi.org/10.1002/bate.201900108

[10] Rolfes, R.; Hübler, C. (2022) *Strukturüberwachung zur Schaffung Digitaler Zwillinge bei Infrastrukturbauwerken* in: Bautechnik 99, H. 6, S. 423–424. https://doi.org/10.1002/bate.202270603

[11] Marx, S.; Wenner, M. (2015) *Structural Health Monitoring (SHM) an der Scherkondetalbrücke: eine semi-integrale Eisenbahn-Betonbrücke* in: Beton- und Stahlbetonbau 110, S2, S. 2–8.

[12] Bartels, J.-H.; Gebauer, D.; Marx, S. (2023) *Einflüsse auf die Messunsicherheit von SHM- Systemen und deren Kompensation am Beispiel von Laser- Distanzmessungen* in: Bautechnik 100, H. 2, S. 67–74. https://doi.org/10.1002/bate.202200102