

Integrated measurement units and sensor systems for harsh industrial applications

Sven Grunwald, Bernard Bäker

Chair in Automotive Mechatronics, Dresden University of Technology

George-Baehr-Straße 1C, Germany

Sven.Grunwald@tu-dresden.de, Bernard.Baeker@tu-dresden.de

Abstract

This paper presents a low-cost methodology of how to integrate measurement units into fiber-reinforced material. Part of this work depicts the manufacturing of encapsulated sensor nodes suitable for harsh industrial applications and enabling condition monitoring plus the collection of measurement values out of the material after the final fabrication of the product itself. Hermetically encapsulated sensor nodes equipped with wireless power supply enable the direct capture of measurement values without the need for additional wires and thus are nearly independent of the location as well as the prevailing environmental conditions. These advantages were opened up as an example for the area of industrial electromagnetic safety brakes commonly used suitable for electric drives.

Key words: Industry 4.0, Internet-of-things, encapsulated sensor node, electromagnetic safety brake, fiber-reinforced material

Motivation and Background

Monitoring the system parameters and the overall condition of an industrial braking system is a very challenging task and is usually called condition monitoring. This includes the wear of the brake disc itself and the state-of-health of the system as well as the air-gap detection between the magnetic anchor and the brake disc. Those values are directly related to the overall function and the performance of the system [1], [4].

On the one hand, it is hard to gather access to measurement points without affecting the whole mechanical system on the other hand it is nearly impossible to measure specific system parameters without the use of expensive add-on hardware like torque shafts. Moreover those additional hardware parts affect the transfer function of the whole system and can introduce problems like noise due to the vibration of loose parts [1], [3], [4]. Nowadays it is possible to manufacture brake rotors out of phenolic-resin-based composite material which is far superior to conventional, metallic materials in terms of load resistance and wear.

These brake discs are finding increasingly suitable applications [1], [2]. In the operation and during the development of a brake system used for safety applications, parameters such as temperature and vibrations are very important. Furthermore, those parameters are

significantly important throughout the whole lifetime of a brake disc. Those parameters change while the brake is in use and can lead to a serious performance decrease which can peak in dangerous states during the operation [2]. Right now, those parameters are only detectable by additional electronic devices and external sensors which are only used in the development state of the system and not always in the final application due to limited space requirements [3], [4].

Within the presented approach, we developed a measurement system which is embedded inside the brake rotor itself. With this solution, it is possible to collect data throughout the lifetime of the brake without affecting the main mechanical functionality of the system.

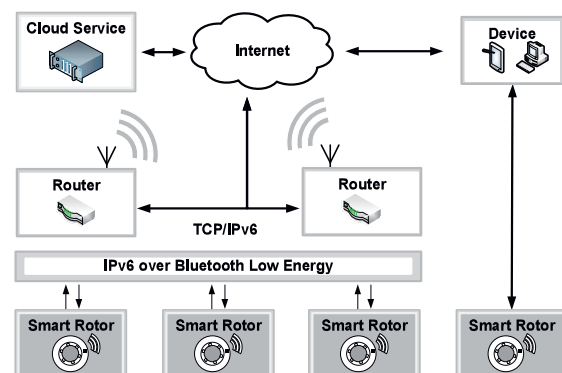


Fig. 1 Smart rotor concept suitable for industrial electromagnetic safety brakes

This paper briefly shows how the integration of electronic, IoT-enabled systems based on a low-cost system-on-chip (SoC) and the required sensor electronics into a composite material is realized. With the aid of this system is possible to achieve a monitoring function right out of the material without the need of large additional mounting parts. Furthermore, this system is suitable for monitoring performance parameters and condition monitoring of the brake disc as well as fulfilling predictive maintenance tasks within the field of electric drives according to the Industry 4.0.

Integration into the fiber-reinforced material

Before starting the integration process with a highly integrated system equipped with sensors it is important to point out that there is actually no test data available to verify the components after using the hot-pressure-method and to validate the sensor data as well as the whole system behavior after the integration step regarding defects.

In general, a SoC is a very complex device consisting of analog and digital circuit elements interacting on a single die manufactured in silicon. A complete structural test of digital parts inside the integrated circuit (IC) is not possible at this point because on the one hand a verified Verilog- or VHDL-netlist of the whole IC is not available for the customer and on the other hand the accessibility of the IC is not given after the integration into the material.

To perform an initial assessment of how far it is possible to integrate an electronic system into fiber composite material without damaging the electronics, simple and manageable digital and analog elements were used [5], [6] and [7]. By using those elements parasitic effects introduced through the fiber-reinforced material itself could additionally be taken into account.

This approach offers several advantages: One can check whether the components are free of defects and withstood the mechanical integration furthermore it is possible to analyze whether the electrical function is negatively affected by the raw material. To verify the whole integration, test methodologies and fault modeling well known from the semiconductor industry were used and adopted for this topic [5], [6].

Within this research the actual integration of the test structures was realized successfully without any serious damage to the components. While using the explained method of the fault model driven test structures the useable component sizes of the passive and active element were identified. Those results are further documented in a previous work [8]

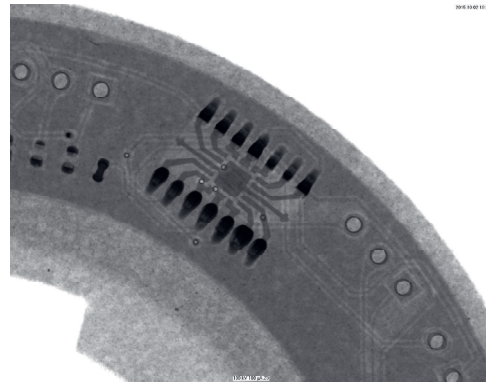


Fig. 2 Analog and digital test structures inside the fiber-reinforced material to verify the manufacturing process

After the successful verification of the test structures by using test vectors and analog test signals based on oscillation it was shown that no devices were damaged during the manufacturing process of the fiber-reinforced material the actual measurement and sensor system was developed [5], [6]. After those positive results the embedded system which should perform the measurement task inside the braking system could be developed.

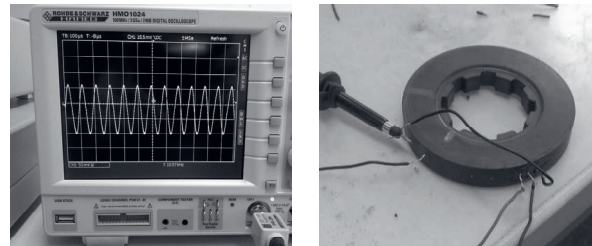


Fig. 3 Oscillation of the analog test structure to validate defect-free integration

Setup of the Measurement Environment

The main processing task within the material should be done by an integrated circuit as before mentioned. Therefore, a SoC is the best choice because a lot of the needed functionality is already embedded within the package of the chip e.g. the necessary RF circuitry for the wireless communication. In addition, the developed embedded system makes use of MEMS-based sensor devices to expand the capabilities of the overall system. The sensors include devices for measuring acceleration in all three axes, three axis gyroscopes measuring the rotation angle, magnetic field sensors and classic temperature sensors. Those sensors are well suited for the task because they are cheap, small and highly integrated into a small package. They are the ideal choice for the integration and to enable the measurement right out of the material. Like already mentioned the SoC provides the needed functionality to communicate with the environment wirelessly.

The data can be recorded from inside the raw material and after the actual measurement the whole data could be compressed and send to a host system e.g. a wireless router. The system characteristics are highly customizable by the user, e.g. the sensor fusion of filter implantation is still possible after the integration process. This is achieved by the implemented over-the-air (OTA) update capability.

As a result, that the SoC supports Bluetooth 4.2 it is possible to equip the embedded system with an IP-address which can be used to connect with the embedded system remotely. Therefore, the smart-rotor could be accessed via the internet, enabling remote diagnosis up to predictive maintenance tasks on the braking system without the need of a technician checking the system and stopping the machine.

While knowing the perfect component sizes and materials withstanding the hot-pressure-method the integration of the embedded system himself was successfully realized. The following picture shows parts of the system inside the fiber-reinforced material after the manufacturing process took place. This also includes the post-hardening process which is necessary for the fiber-reinforced material.

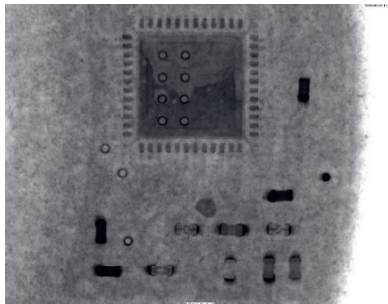


Fig. 4 X-ray photograph of the measurement unit inside the composite material (excerpt)

Sensor Performance and signal quality

Like already mentioned the whole integration process is achieved with the hot-pressure-method for fiber-reinforced materials. This methodology is a well-known manufacturing process for this kind of material. Nevertheless, this method stresses the components because of the high temperature and the high pressure within the actual fabrication. Therefore it is necessary to analyze the system and sensor behavior after the actual integration took place. It is not sufficient to integrate the components free of defects but to measure and test the quality of the sensor signals and the whole behavior. This approach is necessary because MEMS-based sensors are very sensitive to mechanical stress. Already the mounting on the printed circuit board (PCB) plays an important

role. The mechanical and thermal stress, which are exposed to the elements, can cause a performance degradation leading to insufficient measurements in a future application.

One method to analyze a MEMS-based inertial sensor is the Allan variance, introduced by David W. Allan to measure the frequency stability in oscillators [7]. This method can be adopted to characterize MEMS-based sensors and to analyze a sequence of data in the time domain [9]. In the present work, the calculation rules for the evaluation of a MEMS-based sensor on the basis of the Allan variance and their graphical contexts were applied to determine and quantify the different noise terms that exist in inertial sensor data. In general, the Allan variance analysis of a signal in the time domain consists of computing its Allan deviation as a function of different averaging times and then analyzing the characteristic regions and log-log scale slopes of the Allan deviation curves to identify the different noise modes [12].

The major noise relevant terms within this example are the Acceleration-Random-Walk (ARW), the Bias instability (BI) and the Rate-Random-Walk (RRW). The ARW is calculated with the following formula. Within the double logarithmic plot it could be identified through a slope of $m = -0.5$.

$$\sigma_{ARW} = \sigma(\tau_0) \cdot \frac{1}{\sqrt{\tau_0}} \quad (1)$$

The bias instability (BI) appears as flat region around the local minimum of the graph.

$$\sigma_{Bias} = \sigma(\tau_1) \cdot \sqrt{\frac{\pi}{2 \cdot \ln(2)}} \quad (2)$$

The RRW could be identified in a similar way as the ARW. But the RRW appears as with a slope of $m = +0.5$. It is important to mention that this method and the values especially the slope is only valid for MEMS-based accelerometers [12], [13].

$$\sigma_{RRW} = \sigma(\tau_2) \cdot \sqrt{\frac{3}{\tau_2}} \quad (3)$$

The following figures point out a degradation regarding the noise relevant terms after the integration step. This can introduce problems in a further demanding application concerning the sensor resolution.

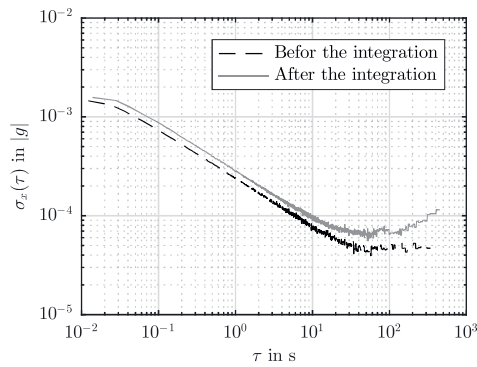


Fig. 5 Allan deviation plot of the X-Axis

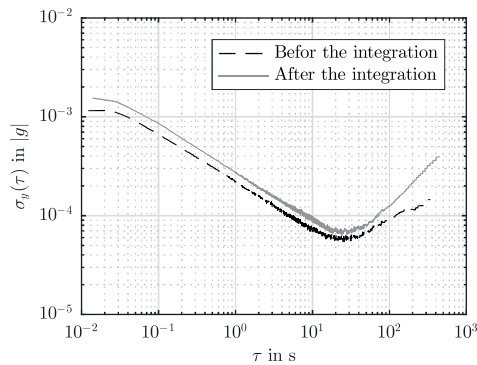


Fig. 6 Allan deviation plot of the Y-Axis

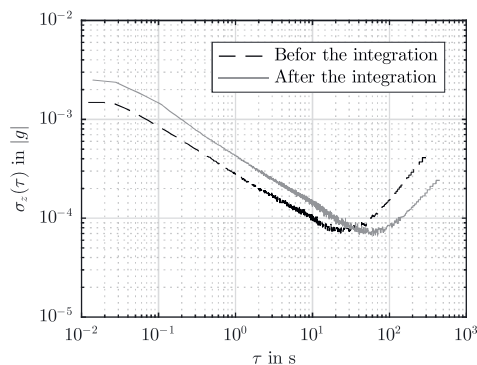


Fig. 7 Allan deviation plot of the Z-Axis

This methodology is well suited to run a sensor related before-after comparison regarding noise terms. The figures 4 to 6 show the computed Allan variance before and after the actual integration step. It is obvious that the mechanical stress changed the behavior of the sensor especially the Z-axis is influenced the most. This is caused by the fabrication process and the pressure along the Z-axis of the sensor. The following table summarizes the results of the Allan variance computation before and after the actual integration step for one sensor axis. Furthermore, the table shows the single noise relevant sensor terms taking the selected system bandwidth into account.

Tab. 1 Noise terms of the MEMS-based sensor in comparison

Before the Integration			
	ARW in mg	BI in mg	RRW in mg / \sqrt{s}
X	2,352	0,129	0,035
Y	2,158	0,131	0,049
Z	2,165	0,134	0,046
After the Integration			
	ARW in mg	BI in mg	RRW in mg / \sqrt{s}
X	2,852	0,159	0,047
Y	2,698	0,165	0,062
Z	3,146	0,198	0,067

System performance after the integration

The system was investigated by using an industrial test stand provided by the project partner. This test bench is usually used for the characterization of brake discs manufactured out of phenolic-resin-based composite material. Therefore, the results achieved on the test stand can be used to compare the smart rotor design with rotors which include no electronics. In the best possible case there should be no major differences concerning the mechanical performance.

The following pictures point out the results for the braking torque after 500 cycles. As could be seen there are almost no differences between the two rotors regarding the braking torque. This leads to the conclusion that the integration does not affect the mechanical performance and the relevant mechanical parameters could also be achieved with a smart-rotor which furthermore enables a condition monitoring right out of the material.

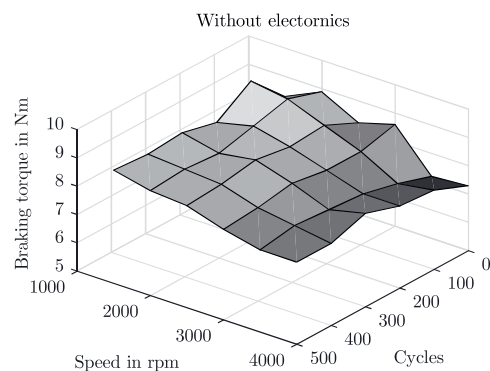


Fig. 8 Rotor without integrated electronics

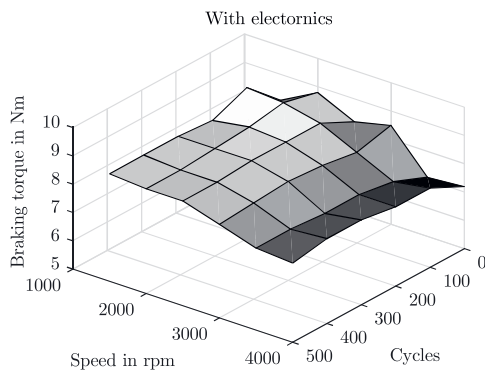
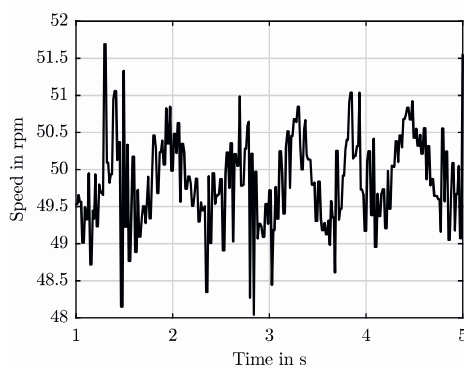


Fig. 9 Rotor with integrated electronics

The following picture shows the measured speed as one representative example right out of the material while using a MEMS-based sensor. The calculation was performed with the raw acceleration data.



The difference in measurement accuracy was quantified under two percent compared to the measured value right at the shaft. The signal quality could also be improved by using digital filtering or by using Kalman-based approaches in further application [14]. This example clearly shows that a measurement can be setup relatively easy with a smart-rotor without the need of external sensors. This approach leads to more data from the system which can be used for controlling and broader tasks.

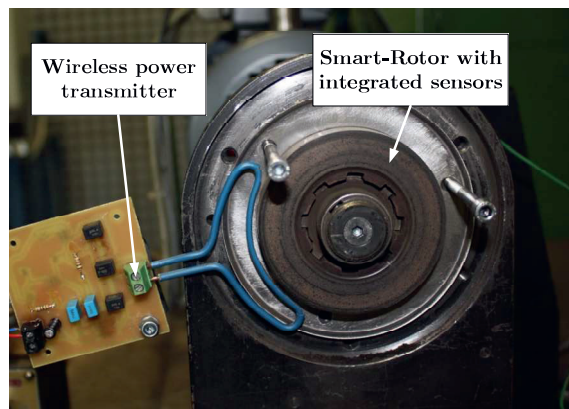


Fig. 10 Smart-rotor inside the test bench to validate the functionality

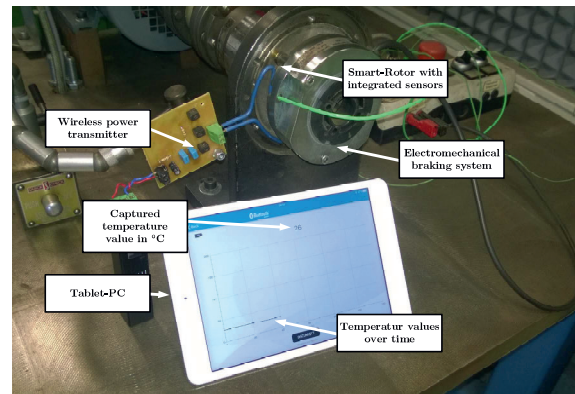


Fig. 11 Smart-rotor sending temperature data captured inside the material to a tablet

Conclusion

The rotor was equipped with a SoC enabling Bluetooth 4.2 communication. Furthermore the system was extended with temperature and MEMS-based sensors. Part of this work was also the integration of a wireless power supply which is used to transfer a small amount of electrical energy into the fiber-reinforced composite material to enable the electronics while the smart-rotor is rotating inside the braking system. The measurements showed that the manufactured rotor is suitable as a friction partner for an electromagnetic safety brake and the mechanical performance is as good as a rotor free of electronics.

Defect-free integration of the measurement unit as well as typical and applications such as shock detection, speed measurement and a temperature monitoring were successfully realized. It is important to mention that those investigated applications represent only a small excerpt of possible and useful applications.

Beyond the actual integration, the quality of the measurement was analyzed by using the method of the Allan-variance. The results show that the integration affects the sensor performance but they are still in a condition to perform a measurement task sufficiently. The developed methodology as well as the fabricated measurement system are a useful supplement in the field of electric drives especially for supporting the important condition monitoring of an electromagnetic industrial braking system up to predictive maintenance tasks. Beyond the presented results, the whole system is upgradable effortlessly to the new Bluetooth 5 standard released in late 2016 by simply upgrading the main processing unit.

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