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Marina SANTO ZARNIK
Franc NOVAK
Gregor PAPA

# SENSORS IN PROACTIVE MAINTENANCE – A CASE OF LTCC PRESSURE SENSORS

# CZUJNIKI STOSOWANE W KONSERWACJI PROAKTYWNEJ – PRZYPADEK CERAMICZNYCH CZUJNIKÓW CIŚNIENIA WYKONANYCH W TECHNOLOGII LTCC

*Sensors are a vital component part of any process-controlled system. Even though designed to properly operate at required conditions within the whole lifetime, all sensors exhibit some level of drift with time. When selecting the sensors for implementation in a system proactive maintenance their ageing in specific operating conditions should be considered as an important issue. Here we focus on thick-film piezoresistive sensors based on low temperature cofired ceramic (LTCC) and discuss their ageing in different regimes of operations. Frequent overloading and particularly with limit overpressures can result in observable drifts and unacceptable scattering from the calibrated characteristics. For the sensors operating in the water the overloads are even more critical. Moreover, under the regime with frequent overloads, some non-critical, intrinsic defects in the sensing structure, which normally do not affect the characteristics and are non-detectable by the output tests in serial production may develop into critical defects that shorten the sensor lifetime.*

***Keywords***: *sensor ageing, pressure cycles, overpressure, low-frequency noise, system maintenance.*

*Czujniki stanowią istotny komponent każdego systemu kontrolowanego przez proces. Chociaż czujniki są zaprojektowane tak, aby prawidłowo działały w wymaganych warunkach w całym okresie eksploatacji, wszystkie wykazują jednak pewien poziom dryfu w czasie. Wybierając czujniki do wdrożenia w proaktywnej konserwacji systemu, należy koniecznie rozważyć ich starzenie się w określonych warunkach pracy. Przedmiotem artykułu są grubowarstwowe czujniki piezorezystancyjne wykonane z ceramiki technologią LTCC (niskotemperaturowej ceramiki współwypalanej) oraz ich starzenie się w różnych trybach działania. Częste przeciążanie, zwłaszcza przy nadciśnieniu granicznym, może powodować dryf i niedopuszczalny rozrzut wskazań w stosunku do charakterystyk wzorcowych. W przypadku czujników pracujących w wodzie, przeciążenia mają jeszcze bardziej krytyczny charakter. Co więcej, w trybie pracy z częstymi przeciążeniami, niektóre niekrytyczne wady wewnętrzne w strukturze sensorowej, które normalnie nie mają wpływu na charakterystykę czujnika i są niewykrywalne w badaniach kontrolnych wyrobu gotowego w produkcji seryjnej, mogą przeobrażać się w wady krytyczne, które skracają cykl życia czujnika.*

***Słowa kluczowe***: *starzenie się czujników, cykle ciśnienia, nadciśnienie, szum o niskiej częstotliwości, eksploatacja systemu.*

## 1. Introduction

Pressure sensors are the third most widely used category of physical sensors in the system maintenance [1]. Beside system control the pressure measurements can be used to reveal physical changes in a system. If the pressure values go outside the expected range, there is a possibility of damaging system parts. In safety-critical systems special measures are taken to provide robust and reliable operation even in the case of sensor failures [7]. Such solutions either introduce hardware or software redundancy, or make the monitoring more complex by enabling it to work better with incomplete data. Not all sensors can be made redundant because of space and cost constraints and the impact of individual sensors on system operation is analysed in order to identify their significance [5]. For the systems that are not necessarily safety-critical but still require reliable operation various possible maintenance scenarios with respect to both reliability and economic criteria are considered. For example, a method used to study the effect of equipment aging under different maintenance strategies is described in [13].

Accurate and reliable sensor measurements are prerequisite for efficient system maintenance, which is also one of the goals of the ECSEL JU project MANTIS – Cyber Physical System based Proactive Collaborative Maintenance [11], and the work reported in this paper. Proactive maintenance (PM) is a maintenance strategy which attempts to anticipate machine failures and similar problems and provides solutions before they occur [3]. The proactive approach benefits from the traditional preventive and predictive maintenance practice and upgrades them by root cause analysis, and predictive algorithms based on cyber physical system models [2, 9, 10]. The proactive maintenance can yield considerable savings over conventional predictive/preventive maintenance programs [4, 14].

Pressure sensors enable monitoring of operating conditions and the wear-out of the critical parts of the mechanical system for which proactive maintenance is performed. Yet, it should be noted that the sensors themselves are not ideal components, but physical devices including sensing elements, electronic components, connections and housings that are aging and degrading [12, 15], and in general may need to be maintained. To improve the reliability of a system, it is essential to ensure reliable operation of the sensors involved, i.e., the correct interpretation of their responses in the different periods of their life-cycles. In this regard, it is prudent to track and monitor their health conditions. In the presented case study, we concentrate on how the operating mode affects their ageing and identify measures that could be taken in defining the maintenance strategy.

The harsh operating conditions accelerate the ageing of sensors. The designers should be aware of this when selecting the appropriate sensors for the target application. Application notes and specifications normally provide data related to standard testing procedures. However, the actual circumstances in practice may impose specific conditions that system designers should be aware of when selecting the appropriate sensors for the target application.

The aging of sensors is an important issue, yet the reports on this are relatively few and mainly for the sensors based on the mature and well-established sensor technologies. In this paper, we present our findings related to the aging of the thick-film piezoresistive pressure sensors realised in Low Temperature Cofired (LTCC) which is a promising technology for wide range of sensor applications [6, 8]. Although a narrow field, the presented results may be helpful to raise awareness in proactive maintenance system design.

## 2. Pressure sensors in PM

Regardless of the specific applications and the complexity of the pressure sensor realizations the sensor itself can be considered as micro/mezzo system which, depending on the physical principle, includes various electromechanical structures (diaphragms, consoles) and the electronics. Pressure sensors can also include sensors of other physical quantities, for example temperature sensors that are used for analog temperature compensation. The aging of a sensor system is highly dependent on the operating conditions (environment, intensity and frequency of loadings) so it would be a good strategy to use PM for the sensor systems themselves. If in addition to the pressure some other variables are measured, such as temperature and relative humidity, such additional information can be used together with the pressure readings for the maintenance of the pressure sensors. The pressure sensors are systems composed of moving parts and functional materials that deteriorate over time. Acquisition and analysis of the sensor readings enables early detection of soft faults resulting from this deterioration.

### 2.1. LTCC-based pressure sensors

Ceramic pressure sensors are in general used in harsh environments and as such can be appropriate for integration in the system proactive maintenance. In this work we consider the thick-film piezoresistive pressure sensors in full Wheatstone bridge configuration realized in LTCC technology. The basic ceramic structure with a thin sensing diaphragm over the pressure cavity and with the integrated channels is made of DuPont 951 green tape. The bridge resistors are made of Du Pont 2041 thick-film resistor material. One representative sample of such sensor and the schematic representation of its cross section are presented in Fig. 1. The basic sensor embodiment can be completed with the readout electronics and may be installed in a housing. Depending on the application the sensors can be protected against harmful effects of the environment and measured media by different protective coatings. In the following we focus on uncompensated sensors without the readout electronics and without the housing. Although housing and protective coating may change the sensor characteristics the trends presented in this paper play important role in practice.

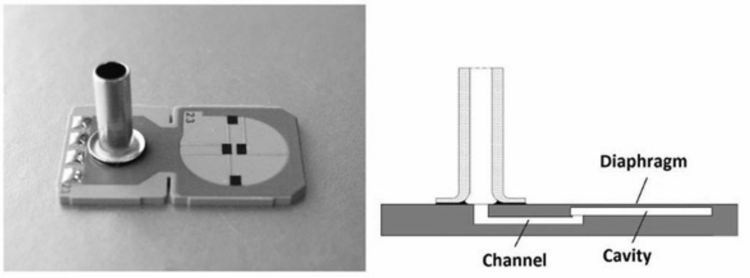

*Fig. 1. Example LTCC pressure sensor and its cross section (not to scale)*

The typical sensitivity (S) of the 100-mbar sensors considered in our case is 14 μV/V/mbar and the long-term stability is better than 0.2% per year. The stability of the offset voltage ($\Delta V = V_{off} - V_{off0}$) at the supply voltage of 5V is less than 100 μV per year. The typical response of the sensor measured in the pressure range from -100 mbar to 100 mbar at 25°C and the relative humidity (RH) of 40% is presented in Fig. 2.

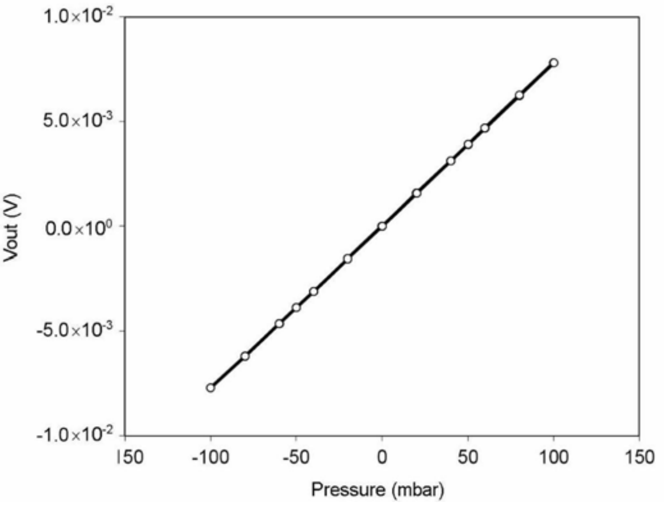

*Fig. 2. Typical response of the 100-mbar sensor measured at 25°C and 40% RH*

Previous studies [16, 17] have shown that the operating conditions in the regime of frequent overloading have non-negligible effects on the aging of such sensors. For efficient maintenance, accurate readings of such sensors including appropriate monitoring of the sensors performances and the operation conditions would be beneficial.

## 3. Ageing of LTCC pressure sensors

This section presents an additional analysis of the experimental results of the earlier case studies (i.e., the feasibility study and the early development phase of several LTCC-based pressure sensors) supplemented by the finding of further experimentation with the prototypes aimed at evaluation of their ageing performances.

It is normally to expect that sensor characteristics change over the time due to the aging of functional materials, even if they are not in contact with harsh media that accelerates the aging process. The aging is therefore highly dependent on the conditions of operation and storage, imposed by the environment (temperature, medium, continuous or randomly changing environment), location and regime of loading. In order to reduce the overall cost of proactive maintenance one might be tempted to employ cheap sensors with low cost housing. However, to assure accurate operation in a long lifetime they should be appropriately protected and maintained.

The LTCC sensors are subject to aging due to the aging of the functional materials and wear-out in long-term operation. The aging of the sensor is also affected by possible intrinsic defects in the material / structure, which in normal operation cannot be identified, but can under certain conditions result in more rapid aging as normally expected. The sensors should be treated as systems with a certain life span, which is heavily dependent on the operating regime as shown in the following.

### 3.1. Ageing due to long-term use and overloads

The pressure sensors are not aging only due to the harsh conditions in which they operate (moisture, temperature), but also due to wear-out effects (the aging of materials due to pressure loads). The situation is similar to that of mechanical parts / systems. Our previous study [16] showed how the offset and the sensitivity characteristics change due to the accelerated ageing with various pressure loads. This article interprets experimental results obtained for the 100-mbar sensors (such as in Fig. 1(a)) in terms of proactive maintenance. The measurements after the loading cycles have shown that at the pressure loads up to full-scale (FS) do not change $V_{off}$ and S critically, and that the scattering of the sensors` readings is acceptably small, while in the case of long-term overloading the drift and the scattering of the readings are much larger. The average changes in the offset voltage of the sensors after accelerated aging (1 million cycles with the pressure loads of 1×FS and 3×FS) measured at 25 °C and 50% RH are presented in Fig. 3. The changes in the sensitivity are shown in Fig. 4.

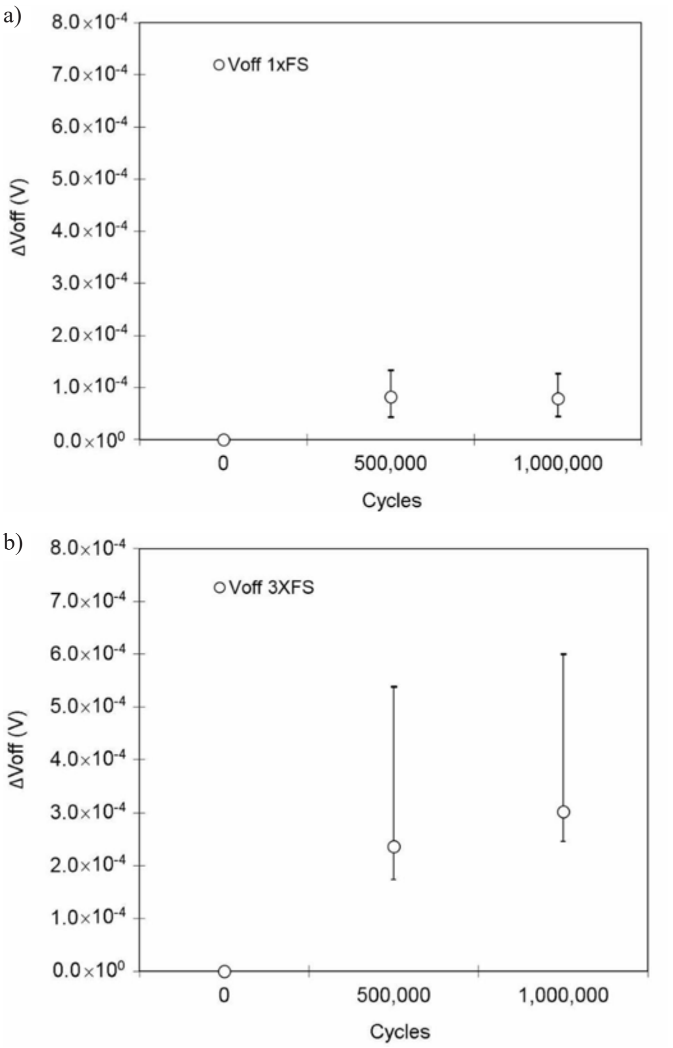

*Fig. 3. Results of ageing tests carried out for the series of 10 sensor samples: (a) absolute value of the changes in the offset voltage ($\Delta V_{off} = V_{off} - V_{off0}$) subjected to the pressure cycles 1 × FS, (b) $\Delta V_{off}$ in the case of overload cycles (3 × FS)*

The above results confirm that the sensors under different loading regimes are aging at different rates. Individual devices may remain good even longer than specified in the producers` specifications, while others are more likely to fall outside the specified accuracy.

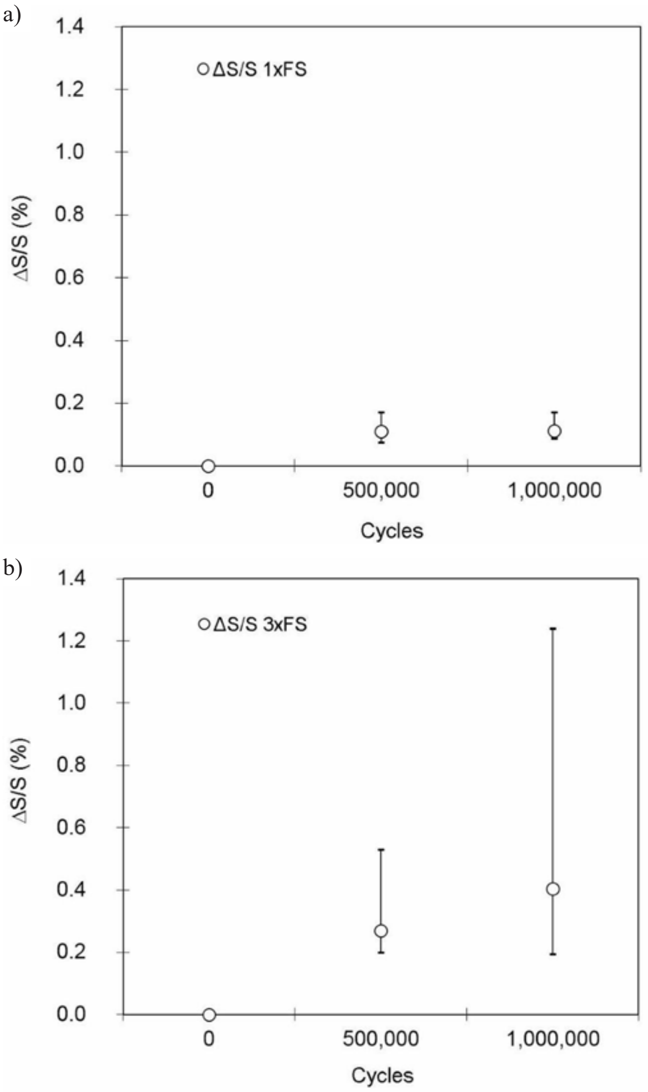

*Fig. 4. Absolute value of the relative changes in the sensitivity ($\Delta S/S_0$): (a) sensors subjected to the pressure cycles 1 × FS, (b) sensors subjected to overload cycles 3 × FS*

Through a series of similar experiments we assessed the influence of the pressure load intensity on the sensors lifetime. The sensors were exposed to the cycles of the full-scale pressure loads and the overloads that they should undergo according to specifications. The changes in the offset voltage and the sensitivity of a series of 100-mbar pressure sensors after accelerated aging (5000 pressure cycles 1×FS, 3×FS and 5×FS in the air at 25°C and 50% RH) are presented in Fig. 5. The sensors which are more often overloaded can have larger drifts from the calibrated response and reasonable extensive scattering of the measured results.

### 3.2. Ageing due to the environment/media

Because of good chemical stability of LTCC materials the LTCC-based sensors can be used for wet-wet applications in different media/environments. However, we should be aware of different ageing effects of the measured media and the harsh environmental conditions. In some media/conditions the functional thick-film structure is aging faster than in the dry air or some inert fluids. Glass-containing ceramics are susceptible to stress corrosion in the presence of humidity so that water can be a critical media. Evaluation of such sensors in the water [17] revealed a slightly worse long-term stability and the reduced burst pressure.

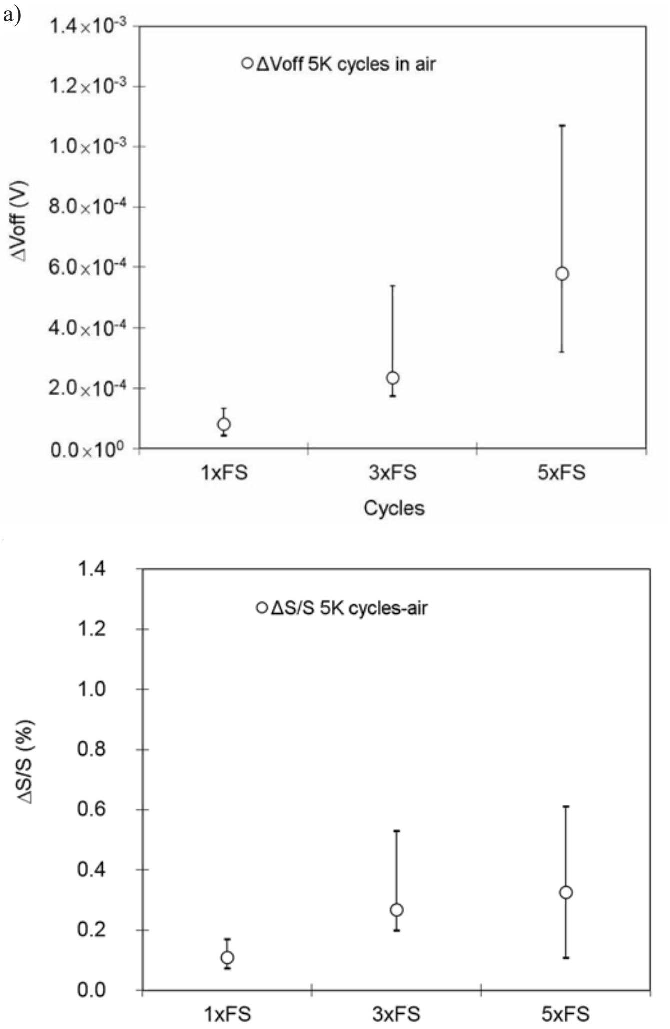

*Fig. 5. Measurements of the sensors exposed to the long-term overloading (5000 pressure cycles) with the different load intensities: (a) The change in the offset voltage and (b) The relative change in the sensitivity*

Comparison of the changes in the offset voltage and the sensitivity of the sensors (shown in Fig. 1(a)) after 1 million pressure cycles in air and in the water are presented in Fig. 6. Notice that the sensors used in this study were not protected against humid environments, and consequently they were disconnected from the power supply during the ageing cycles in the water. Before measurements they were dried in the temperature chamber and stabilized for 24 hours at 50°C.

As evident from Fig. 6, the changes in the sensitivity of the sensor after the loading in the water is significantly greater than after the pressure cycles in the air. Most of the sensors exposed to the pressure loads in the water felt out of the specified tolerances. This implies the reduced lifetime of LTCC sensors in the water. For example, for the required long-term stability of the sensitivity $\Delta S/S_0 < 0.25\%$, the sensor that otherwise may normally withstand one million cycles in the air will fail at the same load in the water.

Taking into account these findings when designing new applications, a sensor can be optimized so that the operation in the water does not critically degrade its reliability. Still, it is important to be aware that the drift of the readings of the sensor operating in the water (due to normal aging and frequent overloads) can be significantly higher than expected for the loads of lower intensity and/or for the operation in the air.

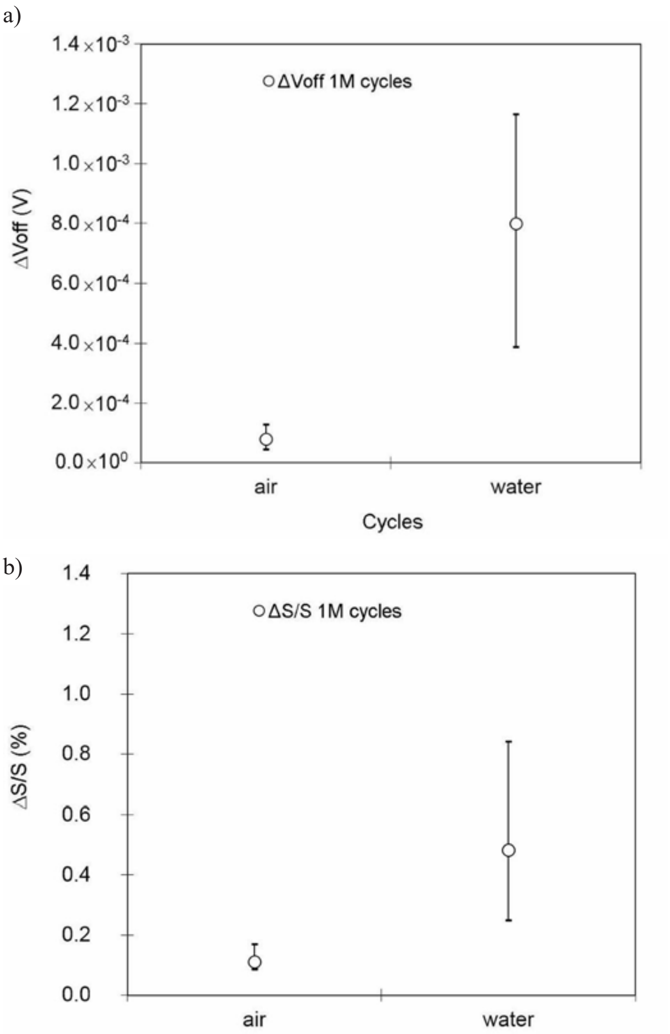

*Fig. 6. Characteristics of 100-mbar LTCC sensors after 1 million FS pressure cycles in the air and in water. (a) Changes in the offset voltage, (b) The average relative change in sensitivity.*

### 3.3. Ageing due to intrinsic irregularities

As showed in [16] the stability of the sensors' offset voltage and the sensitivity are related to the low-frequency noise of the output signal. A lower noise level corresponds to a better long-term stability while the sensors with higher noise of the output voltage may have poor long term stability.

It may happen that same sensors have small intrinsic irregularities/defects in the material structure which are not detected by typical output tests in serial production. Such sensors are still operating within the specifications, however, experiments showed that irregularities in the thick-film structure may affect their long-term stability and shorten the sensors lifetime.

The low frequency noise of the sensors with small irregularities is typically higher than the noise of the perfect sensors without any irregularity. The measurements of the sensors with small irregularities in the thick-film resistor structure showed for about 30% higher low-frequency noise. As long as the sensor resolution (which is reduced due to the increased signal noise) remains within the range required by application, the higher noise is not critical.

The experiments carried out through the accelerated ageing of a series of 100-mbar LTCC-based sensors, which were subjected to the series of pressure cycles showed that the long-term loading does not cause significant changes in the sensors' signal noise. The situation is evident from Fig. 7 which shows the intrinsic low-frequency noise of the output signal measured before the ageing cycles and the resulting changes in the offset voltage and the sensitivity after the pressure cycles of intensity full scale range (FS) and the overload pressure of intensity of 3 times FS (3×FS).

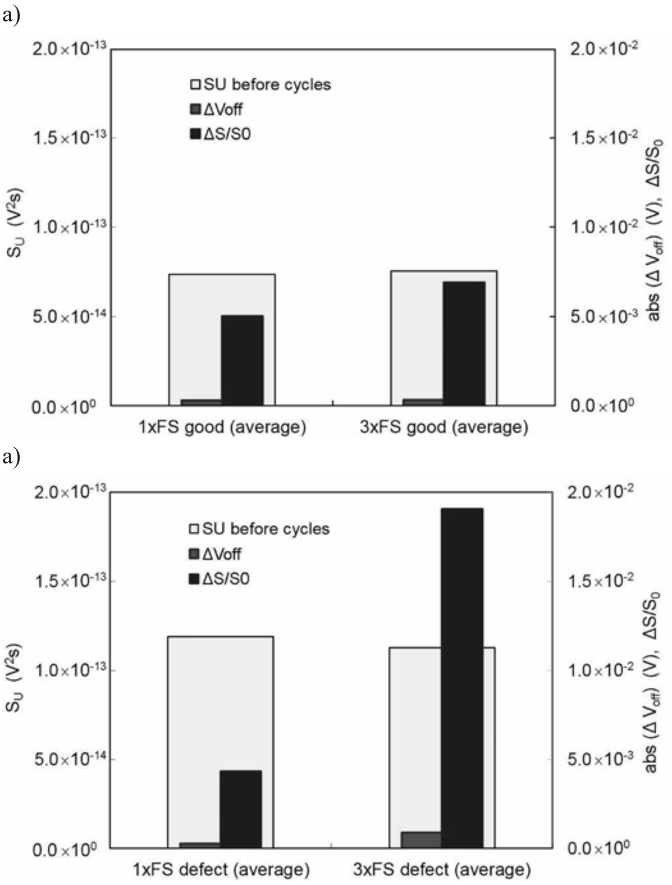

*Fig. 7. Average value of the low-frequency noise of the output signal ($S_u$) measured before the pressure cycles and the changes in the offset voltage and the sensitivity after pressure cycles of intensity 1×FS and 3×FS: (a) the sensors without any defect, (b) the sensors with the defects*

Fig. 7(a) shows that the frequently overloading of the sensors with the relatively low noise ($< 1e^{-13}$ $V^2s$) may lead to (in most cases) not critical changes in their sensitivity. The experiments also revealed that the sensors with the intrinsic irregularities have the low-frequency noise > $1e^{-13}$ $V^2s$ (Fig. 7(b)). Measurements of those sensors subjected to overload cycles showed significant drift of their characteristics. As can be seen from Fig. 7(a), the sensors which are free of a defect normally undergo such pressures.

Consequently, the sensors with a higher noise should not be overloaded because operation in such conditions critically impacts their life span. Any irregularities in the structure of the sensor may prove to be hazardous because they can lead into critical defects and the sensor falls out of tolerance. The experiments showed that the pressure cycles of the sensors with small irregularities critically degrade only those sensors which have been overloaded. This suggests that the noise measurements can be used as a successful pre-screening test for a quick assessment of the sensors` long-term stability.

## 4. Discussion

Based on the above experimental results the following measures have been identified for preventive and predictive maintenance strategies that support the target proactive maintenance.

As regards the preventive maintenance, cyclical maintenance actions should be planned, such as checking the sensor offset after a certain time of operation or a specified number of cyclic loadings. Such subsequent assessment of the sensor´s post occupancy performance makes it possible to examine the interventions planned at the design phase in the light of its actual in-use needs. The subsequent cyclic inspection of sensors health can also include the measurement of the noise of the output signal. As follows from the results presented in 3.3, even a single noise measurement before using the sensor in can be a good indicator of how often the sensor needs to be checked. In this way the offset of the sensors with the high noise ratio of its output signal should be checked in shorter time periods.

The predictive maintenance strategies include the planning of cyclic inspections. In this context regular inspections are carried out to monitor the performance of the design solutions over time and their performance after any intervention. In the above presented case of the LTCC sensors further maintenance actions can be planned after inspection of the sensors offset depending on its degradation level. The larger changes in the offset value mean that the sensor will be out of the required tolerances in a shorter time and need to be regularly inspected after a shorter period. Furthermore, if in addition to the mentioned cyclical inspections, we also collect data giving information about the sensor operating mode (e.g. the frequency of overloads), we can further improve the estimation of the time until the next inspection. As shown in 3.1, 3.2 and 3.3 frequent overloading speeds up the aging of the sensor in all cases.

## 5. Conclusion

The aging of sensors depends on the measured medium/surroundings as well as on the regime of operation. From the proactive maintenance strategy point of view, we studied the aging of LTCC-based pressure sensors under different operating conditions. In this paper, we show how the sensor response changes due to the long-term operation in the normal conditions and how it's "expected" ageing is affected by the frequent overloading in different environments (i.e., in the air and in the water). We discuss how the aging of LTCC pressure sensors is affected by the long-term operation in normal conditions and under specific conditions with frequent overloading in the air and in the water. In practice, the sensors can withstand a number of overloads (under burst pressure), but at the same time they are aging faster than expected which should be considered in system maintenance. The frequency and intensity of overloads can result in larger drifts from the calibrated response and larger scattering of the measured results. In the water, the overloads are even more critical. Frequent overloading reduces the lifetime of the LTCC sensors more than overloading in the air. In addition, possible intrinsic defects non-detected by the output tests in serial production may also shorten the sensor lifetime under the operation with frequent overloads. Non-negligible effects of aging should be taken into account when selecting the components for proactive maintenance. The proposed measures can be considered also in other sensors/technologies and serve in general as guidelines for implementing maintenance strategies.

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**Marina SANTO ZARNIK**
**Franc NOVAK**
**Gregor PAPA**
Jožef Stefan Institute
Jamova ulica 39, 1000 Ljubljana, Slovenia

E-mails: marina.santo@ijs.si, franc.novak@ijs.si, gregor.papa@ijs.si