Strategies to Enhance Signal Validity and Extend Reliability of High Temperature Sensors Especially for Pressure and Acceleration

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ABSTRACT

Measuring pressure and acceleration at temperatures of 600°C and higher usually limits the applicable technologies to piezoelectric sensors. Robust sensors for combustion control or measuring vibration levels at these temperatures have been available for years but the validity and the reliability of the signal are frequently not on a level that they could easily be used to generate reliable data for engine health. Sensitivity change with temperature and sensitivity deviations from production could add up to considerable error margins, making it difficult to decrease safety margins without extensive calibration of the measurement chain and including other physical parameters like thermal gradients.

Enhancing the reliability of the signal can be achieved by several means and proven strategies will be detailed in this paper. The underlying design principles that favor piezoelectric technology over other technologies will be elucidated in detail and advantages of piezoelectric single crystalline materials are highlighted. Especially the advantages of gallium phosphate (GaPO4) based sensor technology, which outperforms conventional piezoelectric materials such as quartz and tourmaline because of its outstanding temperature stability and lack of pyroelectricity are presented. These material properties in combination with application optimized transducer design allows for miniaturization of high-temperature pressure transducers as well as additional measurement of acceleration without increasing the system complexity or maintenance efforts. Lastly, laser vibrometer studies for direct optical investigations of the mechanical properties of the transducer and the influence of the cable assembly are presented, which further improves the reliability of the entire measurement chain, especially with regard to on-board use.

1.0 INTRODUCTION

In recent years, there is an increasing demand for miniaturized pressure sensors (more generally transducers) with a higher precision at highest temperatures and high pressures. These requirements often cause problems to the transducer design and materials. The sensitivity decreases significantly with temperature and temperature changes cause interference to the sensor signal. Pressure transducers are widely used to measure static and dynamic pressure changes. Dynamic pressure changes or pressure pulsations are of special interest for combustion processes in reciprocating engines or gas turbines in order to improve efficiency and reduce emissions. However due to the nature of combustion, mounting temperatures can reach easily 600°C and more under normal operation conditions.

For lower temperatures, up to approximately 200°C, a multitude of pressure sensing solutions exist. Often the principle is based on strain gauges which detect pressure based on changes of the electric resistance due to geometric deformations or because of the piezo-resistive effect. Also, pressure transducers based on the change of the capacitance caused by mechanical deformation of sensing elements are often used. The fabrication of piezo-resistive and capacitive sensors typically requires microfabrication technologies because of their miniature size and thus are often referred to as microelectromechanical systems (MEMS). However, due to the materials in use, such as silicon and various polymers, the temperature range is limited to approximately 150°C.

While these technologies work very well for measurements in typical environmental conditions, pressure sensing gets more challenging at elevated temperatures. Above 200°C the selection of suitable materials which withstand such demanding environments is rather limited. For high temperature applications in the region of 700°C the use of pressure transducer based on the piezoelectric effect are preferable since the involved materials such as gallium phosphate and nickel-based superalloys are able to withstand such harsh conditions.

2.0 PIEZOELECTRIC TECHNOLOGY

2.1 Direct piezoelectric effect

In short, piezoelectricity is the physical phenomena of certain materials, mostly crystalline, to show an electric polarization if an external force is applied to the material [1]. Forces induce mechanical stress within the crystal which leads to minor deformations and in turn cause a macroscopic electric polarization due to the specific atomic arrangement. Hence, only crystalline materials without an inversion center (non-centrosymmetric crystal classes) show piezoelectricity. The electric polarization can be detected as the corresponding flow of charges which is necessary to compensate the electric field within the crystal. Therefore, the opposing crystal surfaces must be electrically connected since the crystal itself is ideally non-conducting. This is achieved by applying metal electrodes as thin films, usually by sputtering precious metals.

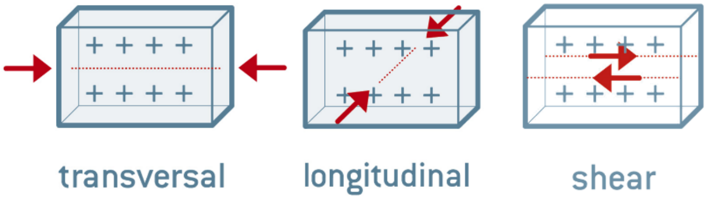

Figure 1: Different piezoelectric operations modes depending on the direction of the applied force (red arrows) and polarization directions (indicated by + symbols on the respective crystal faces) are illustrated. Depending on the application the use of the transversal or longitudinal mode allows for an optimized design of pressure transducers.

Since the amount of charge is proportional to the applied force, the corresponding proportionality constant is known as the piezoelectric constant *d*. An applied force can compress (normal to crystal surface) or shear (parallel to the surface) a material. Therefore, various piezoelectric constants *d* are listed for materials which depend on the type of stress and direction of the electric polarization (piezoelectric tensor). For pressure sensing applications, the so-called longitudinal and transversal compression modes are most important (see Figure 1). To obtain the desired piezoelectric response, the crystal cut direction is crucial as it defines upon which crystal surface the force will be applied. Thereby the piezoelectric response i.e. piezoelectric constant *d* can be selected.

In the longitudinal case, the polarization response is parallel to the stress, meaning the charges are collected on the same surfaces as the force is acting on. The generated charges are directly proportional to the piezoelectric constant for this mode regardless of the crystal size. In contrast, using the transversal effect, meaning the charges are collected at the surfaces perpendicular to the external stress, the generated charge depends not only on the corresponding piezoelectric constant but also on the crystal geometry (height-to-width ratio).

2.2 Crystal element design

Considering the two piezoelectric operational modes, longitudinal or transversal, allows for customizing pressure transducers with specifically tailored crystal elements that fit best to the intended application. In order to utilize the transversal effect, the sensing elements must be fabricated as elongated bars since the height-to-width ratio is decisive for the superior sensitivity. Therefore, only single crystalline materials of highest quality can be used since piezoceramics or defect-prone crystals are not able to withstand the structural demands. Due to the high uniformity of industrially grown gallium phosphate crystals, the material is well-suited for the fabrication of transversal sensing elements (transversal compression mode, Figure 2). While the piezoelectric material constant is fixed, the height-to-width ratio of the crystal bars can be tuned to achieve the necessary sensitivity and resolution for precise pressure measurements or robustness for increased longevity.

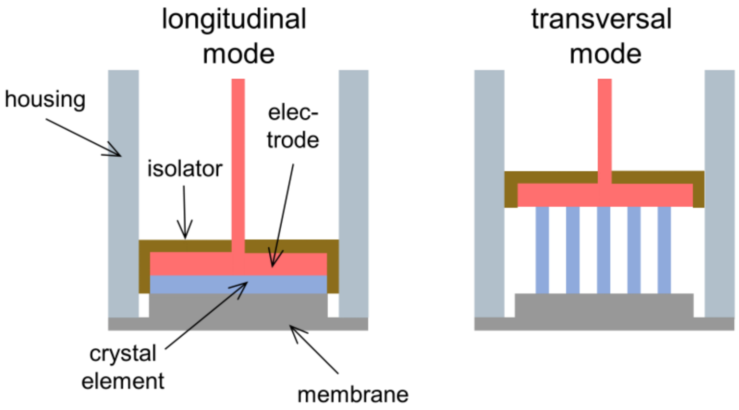

Figure 2: Illustration of piezoelectric pressure transducers based on longitudinal (disk-like crystal elements) and transversal mode (bar-shaped elements).

In contrast to the transversal design, the longitudinal design employs disk-like crystal elements (see Figure 2), which is less demanding on the crystal quality and can be realized using single crystal materials as well as piezoceramics. For the harshest conditions, such as extreme vibrations, pressure and temperature gradients or in case operational reliability is paramount, the longitudinal design offers an advantage since it allows for the stiffest and most robust pressure transducers. The main drawback is usually lower sensitivity since the only option to increase the charge output is by stacking multiple crystal disks. In the rare case of shattered crystal discs due to massive stress events such as unexcepted shockwaves, the sensors will usually remain operational since the crystal disk is sealed within the transducer. Hence such a sensor will not compromise the application for example generating a leak in an otherwise sealed combustion chamber even under extreme overload conditions.

Anyhow, selecting a specific crystal design is always a compromise between signal quality and robustness. The importance is having access to various design options to choose or develop the optimal pressure transducers for the intended application.

2.3 Single crystalline gallium phosphate ($GaPO_4$)

Gallium phosphate ($GaPO_4$) is a piezoelectric crystal which has been developed for the production of pressure transducers allowing miniaturization and high thermal stability without cooling, while maintaining high sensitivity and accuracy [2]. It belongs to the same point group as quartz, therefore the lack of pyroelectricity guarantees that temperature changes do not cause misreadings. Moreover, it does not exhibit a quartz-like α-β phase transition, meaning the thermal behavior as seen in Figure 3 is reversible even for high temperatures since crystal twinning does not occur. The $GaPO_4$ crystal lattice is extremely stable and the piezoelectric coefficient remains virtually constant up to a phase transition at 970°C.

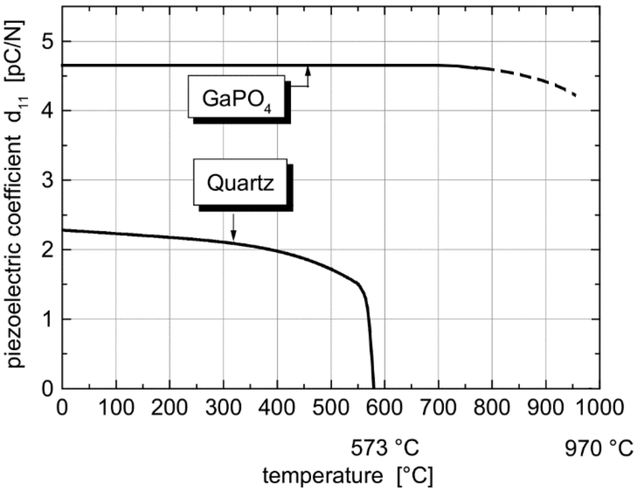

Figure 3: Temperature dependency of the piezoelectric constant d_{11} of quartz and $GaPO_4$. While quartz loses its piezoelectricity already at lower temperatures, $GaPO_4$ shows virtually no deviations from room temperature up to 800°C making it ideal for high-temperature applications.

$GaPO_4$ has been used to produce pressure transducers for several years and the manufacturing experiences together with industrial crystal growth facilities helped to make it available for numerous applications. The most remarkable feature for applications using the piezoelectric effect of $GaPO_4$ is the temperature stability of the piezoelectric coefficient d_{11}. It does not deviate significantly from its room temperature value of 4.5 pC/N, about twice the value of quartz, up to 500 °C and stays within few percent of that up to 700 °C (Figure 3).

This means that exceptional temperature stability can be achieved for piezoelectric sensors of longitudinal compression type (d_{11}), transverse compression type ($d_{12} = -d_{11}$) and shear type ($d_{26} = -2\ d_{11}$).

Due to the high homogeneity of hydrothermally grown crystals compared to crystals grown from the melt the variation of materials properties due to the growth process is minimized which translates into a very low deviation of the individual transducer sensitivity.

2.4 Piezoceramics

A different pressure sensing approach is based on piezoceramics. Instead of using single crystalline elements, ferroelectric polycrystalline ceramics such as lead zirconate titanate (PZT) are polarized by an external electric field to make the piezoelectric effect usable [3]. The upper temperature is limited by thermal depolarization of the piezoceramic which is approximately 200°C. Despite the gradual depolarization with increasing temperature, ferroelectric domains might spontaneously depolarize which causes large signal spikes. These charge spikes, often called pulse-noise or “pop-corn” effect, are particularly difficult to handle since they are capable of overloading the charge amplifier which leads to signal dropouts. Hence, continuous monitoring or control loops cannot be easily implemented with piezoceramic based transducers without taking the “pop-corn” effect into account.

Since most piezoceramics are ferroelectrics they are inherently pyroelectric (see Figure 4 and 5). Pyroelectric materials show an internal electric polarization when exposed to temperature changes. Thus, ferroelectric materials generate charges when deformed (piezoelectric effect) and when subjected to temperature gradients, making it difficult to measure pressure reliably. While piezoceramics show considerably higher sensitivity (pC/bar) compared to single crystal elements, the actual signal quality will be compromised by the aforementioned effects making them less suitable for high quality pressure transducers.

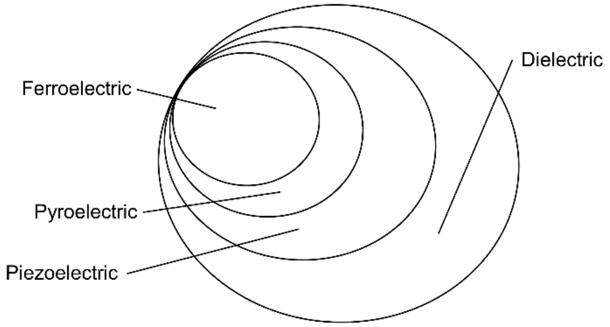

Figure 4: Classification of materials based on their response to external stresses. Ideal pressure sensing materials should only respond to pressure changes, such as e.g. single crystalline gallium phosphate or quartz. For example, pyroelectric materials, despite being piezoelectric, respond also to thermal gradients, making them less suitable for pressure sensing.

3.0 TEMPERATURE CROSS-SENSITIVITY

3.1 Pyroelectricity

Even if perfectly compensated for thermal expansion, some piezoelectric materials might also show a polarization response to temperature changes due to their inherent pyroelectricity [4]. This additional polarization will interfere with the polarization connected to the piezoelectric effect which is used to detect pressure changes. Because of the pyroelectricity the additional signal caused by the temperature gradient is superimposed on the pressure signal as illustrated in Figure 5.

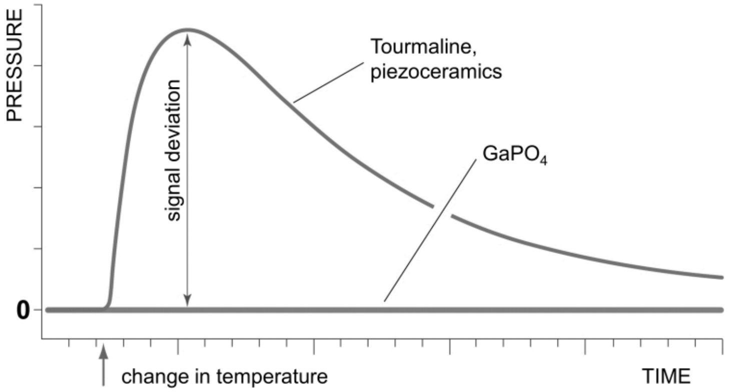

Figure 5: Illustration of the pyroelectric effect causing a false pressure signal created by a temperature change. $GaPO_4$ based pressure transducers are not susceptible to interference caused by pyroelectricity allowing for reliable measurements also during temperature gradients.

The undesired response to temperature changes is especially problematic during transient operating conditions where temperature has not stabilized yet. Such transient conditions are typically present in gas turbines during start-up or load changes making pressure monitoring during these times with pyroelectric materials such as tourmaline or ceramics unreliable. The pressure signal will be compromised especially in the low-frequency range (see Figure 6) and thus cannot be used for critical monitoring or control tasks during transient condition.

In contrast, due to the lack of the pyroelectric effect gallium phosphate based piezoelectric sensors operate reliably even in transient conditions, meaning uninterrupted pressure monitoring is possible and enables new applications including e.g. flame-out detection or ignition monitoring.

3.2 Minimizing temperature cross-sensitivity

To study and optimize transducers with regard to the temperature cross-sensitivity or radiated heat, a transducer is periodically exposed to a heat source using a chopper wheel. During the test the pressure is kept constant, therefore contributions due to actual pressure changes can be excluded. Such an experimental setup allows for the determination of the thermal sensitivity of various piezoelectric materials as well as different transducer designs. Of particular interest is the frequency dependency since the thermal contributions are of dynamic nature as well.

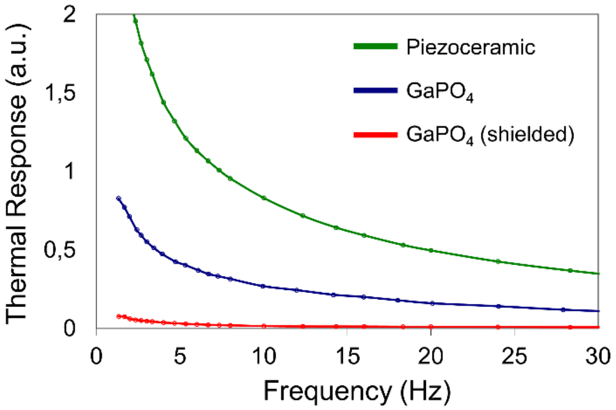

Figure 6: Signal caused by exposure to radiated heat for different pressure sensors based on single crystalline gallium phosphate (GaPO4) and piezoelectric ceramics (green). The GaPO4 based sensor (blue) shows a considerably lower response to thermal gradients (lower thermal cross-sensitivity) which can be further lowered by adding a heat shield (red line).

Figure 6 shows the comparison of typical signal deviations between piezoceramics and gallium phosphate based sensors. The piezoceramic type (green) shows significantly larger deviations compared to gallium phosphate (blue). Especially in the low frequency region, the deviations are most pronounced. The increasing deviation with lower frequencies can be explained by the larger temperature change during each chopper wheel rotation since the sensor has sufficient time to transfer enough heat to its surroundings and thereby reducing its temperature before the next heat exposure. With increasing frequency, the thermal inertia of the system will dominate and the system will steadily approach a constant average temperature and thus the pyroelectric contribution is vanishing.

Using an additional thermo-protection such as a flame arrestor (Figure 6, red line) in front of a pressure transducers reduces the measuring artefacts even further as it protects the membrane from the thermal shock. As an alternative to metallic flame arrestors, a polymer heat shield based on polysiloxanes (silicone) can be easily mounted (e.g. clipped into a small groove) in front of the membrane as illustrated in Figure 7. The silicone heat shield will gradually deteriorate because of the heat but in turn will allow for very precise measurements for a limited time span such as for R&D applications. After the silicone heat shield is burned off, the transducer is still fully operational, however with its original thermal cross-sensitivity. Nevertheless, the silicone shield can be easily replaced for subsequent measurements.

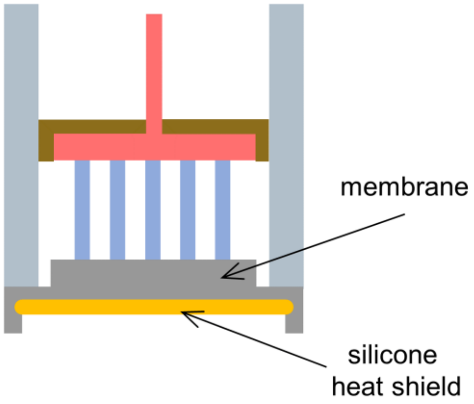

Figure 7: Silicone-based heat shield (yellow) mounted in front of the pressure transducer membrane to reduce the thermal cross-sensitivity.

4.0 FREQUENCY RESPONSE USING LASER VIBROMETRY

The frequency response (or transfer function) of a pressure transducer is a crucial dynamic parameter for the signal quality. For highest signal quality, it is required to operate the transducer in the flat region of the transfer function. This means, that the ratio between the signal input and output is independent of the signal frequency. Otherwise, certain frequency ranges might be attenuated or amplified which makes meaningful signal analysis (such as FFT) impossible. Due to the housing, packaging and attached cable assembly, resonances may be present which lead to deviation of an ideal flat transfer function and causes a signal distortion. This makes it necessary to carefully investigate the frequency response of the pressure transducer itself and the complete setup including the attached cable assembly. A highly sensitive method to study vibrations and resonance behavior which is based on optical laser interferometry is known as laser vibrometry.

4.1 Membrane oscillations

Typically, the frequency response and hence the resonances of a piezoelectric transducer are determined by applying a sinusoidal signal of constant amplitude and varying frequency. Recording the output signal of the transducer will give the frequency response. However, generating an input signal with constant amplitude over a sufficiently wide frequency range is extremely challenging due to the high resonance frequencies of piezoelectric transducers [5].

An alternative approach, similar to an electric impedance scan, is based on electrical excitation using the inverse piezoelectric effect, meaning the transducer is operated as an actuator driving the membrane. Instead of recording the electrical impedance of the system, the membrane response is determined optically using a laser vibrometer. Vibrometry can also be used to study the natural response (free oscillations) to mechanical excitations such as a defined hit with an impulse hammer (approximated □-function). In addition to the simple frequency response, the scanning mode allows for the visualization of the actual oscillation modes as depicted in Figure 9 [6]. Knowledge of the actual membrane oscillation modes helps with optimizing the design to avoid additional mechanical resonances aside from the crystals main piezoelectric resonance due to the coupling of mechanical and electrical energy.

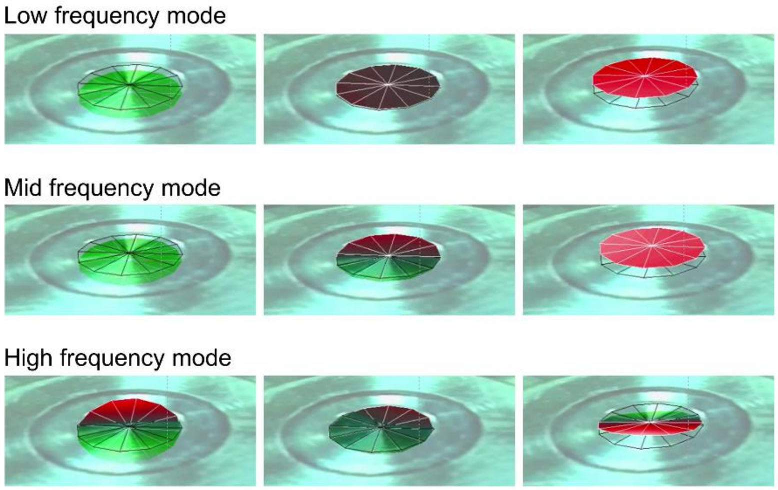

Figure 9: Laser vibrometer investigations of a pressure transducer membrane showing different oscillations modes depending on the frequency. The membrane geometry can be optimized to avoid resonances which lead to non-linear behavior.

4.2 Cable assembly resonances

Besides the characteristic piezoelectric resonance due to the coupling of the mechanical and electrical energy, a scanning laser vibrometer can be used for investigating the influence of the cable assembly on the frequency response. The experimental setup is depicted in Figure 10, showing the individual scanning points on the cable and transducer. The transducer is mechanically excited using a shaker with varying frequency along the z-direction (perpendicular to shaker plane). While the transducer without attached cable assembly will only be subjected to accelerations along the same direction as generated by the shaker, the cable assembly will introduce additional forces and interfering signals which are highly frequency dependent.

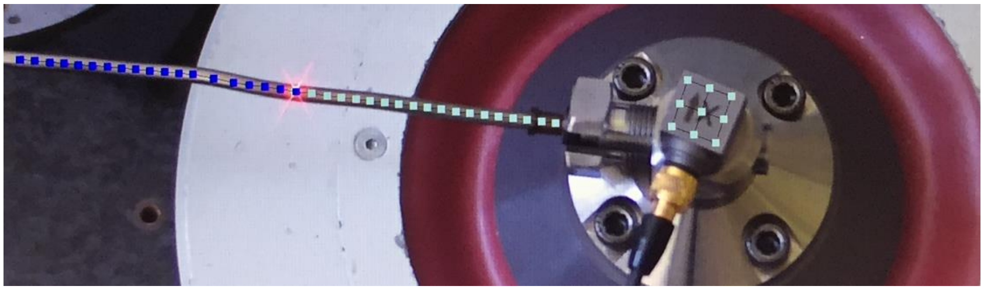

Figure 10: Setup of laser vibrometry to study the resonance behavior and influence of metalic hard line cables on a pressure transducer. The transducer is mounted on a shaker below the reference accelerometer. Blue and green squares indicate the scanning points of the laser vibrometer.

Figure 11 shows the response for different resonances at 8 kHz and 10 kHz. In the first case, the transducer mainly sees accelerations along the z-axis which is expected (transducers plane parallel to x-y plane). However, the cable oscillations at 10 kHz also introduce also additional accelerations perpendicular to the driving force as seen by the significant tilt of the transducer plane. Such complex interplay between individual parts of the measurement chain might stay undetected if extensive testing is not conducted. While a standard shaker test allows for identifying resonance phenomena within the transducer, only the additional information obtained by laser vibrometer studies provide insights which are necessary to conduct further design improvements. In order to avoid unwanted effects, the cable assembly should be prevented from moving or oscillating. Furthermore, increasing the stiffness of the transducer housing and cable connectors will shift the resonances of the transducer to higher frequencies, meaning the cable oscillations are less likely to excite transducer resonances which interfere with the pressure signal.

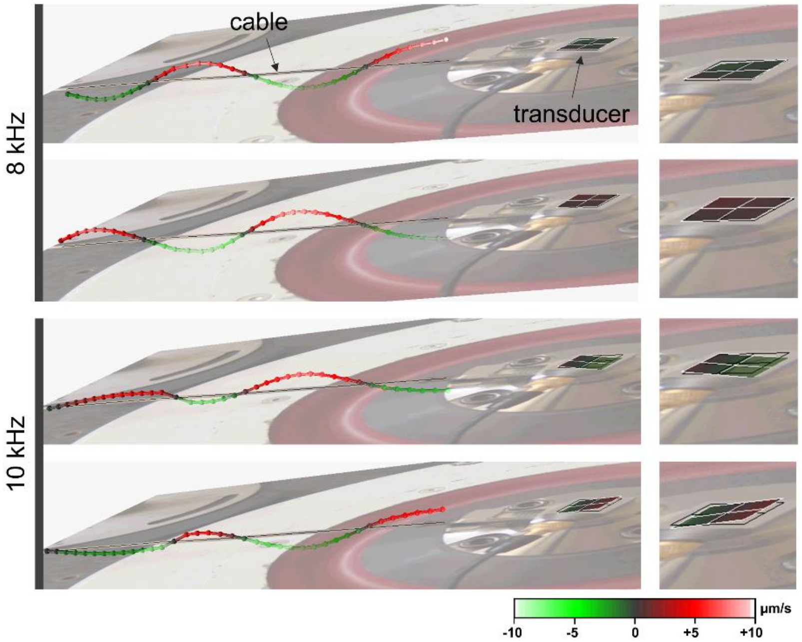

Figure 11: Resonance behavior of a cable assembly and its influence on the attached pressure transducer derived from laser vibrometer investigations (red and green areas indicate the vertical speed of the cable and transducer, respectively). Depending on the oscillation mode, resonances within the transducer can be excited by the cable (transducer tilt at 10 kHz) and interfere with the pressure signal.

5.0 MINIATURIZATION OF PRESSURE TRANSDUCERS

Especially for on-board use as well as R&D applications mounting space is a decisive factor for selecting suitable transducers. In automotive applications, the cylinder pressure is an important parameter to optimize the performance of reciprocating engines. The best option is to directly measure the pressure within the cylinder, which requires the pressure transducer to be mounted on the cylinder head. Since, available space for additional instrumentation is extremely limited in this particular area, the design of in-cylinder pressure transducers was always focused on minimizing the mounting dimensions. Nowadays, transducers with 5 mm mounting threads are commonly used in engine test beds and even during on-board use in motorsports for critical monitoring tasks. For the most constrained environments, versatile transducer with 3.5 mm mounting threads are available.

Benefiting from the experience in miniaturization of automotive transducers and having experience in high-temperature design allows also for miniaturization of high-temperature pressure transducers as used for flame pulsation monitoring in gas turbine combustors (see Figure 12). The main difference in the requirements of in-cylinder measurements and pulsation monitoring are the operational conditions. While the expected temperatures in gas turbines are typically a few 100°C higher compared to conventional automotive engines the requirements regarding the pressure range are lower due to the lack of massive pressure shockwaves as caused by knocking events or pre-ignitions. Thus, the membrane and crystal elements can be optimized for these specific conditions which allows for compact designs with 5 mm housing diameter and operational temperatures up to 600 °C.

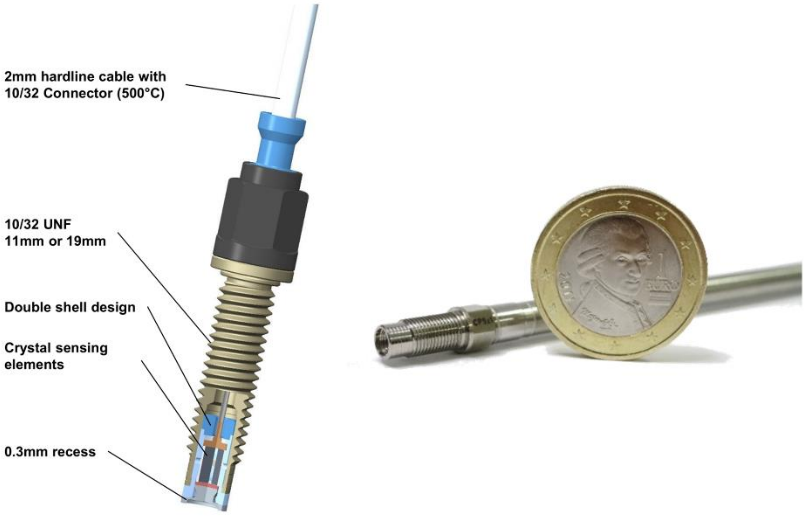

Figure 12: Miniaturized high temperature pressure transducer (Piezocryst CP5x1 Series) with approximately 5 mm diameter (M5 or 10-32 UNF thread).

A significant advantage of miniaturized transducer design is a greater flexibility to choose a perfect mounting position and overall reduced weight. Often due to limited access or overall design restrictions the sensor can only be placed in certain areas without taking signal quality into account. Having more flexibility in the positioning of the transducer, allows for choosing the optimal transducer placement regarding signal detection and protection from various adverse influences such as strong electromagnetic fields. Hence, the unavoidable loss in sensitivity due to miniaturization of the crystal elements is well compensated by an improved of signal detection. In general, a miniaturized sensor will always be less intrusive and introduces only minor deviations to the original apparatus design, meaning the intended operational behavior is unaffected.

Mechanical stresses transferred through the mounting bore and thread can be problematic for miniature pressure transducers since these external forces might change the defined preload of the crystal stack which leads to unreliable pressure readings. By introducing an additional inner shell around the crystal elements, as implemented in the Double Shell$^{\text{TM}}$ construction (see Figure 13 left), the external influence is minimized. The outer housing and the inner shell are separated by a small gap which decouples the sensitive crystal elements from adverse external mechanical stresses.

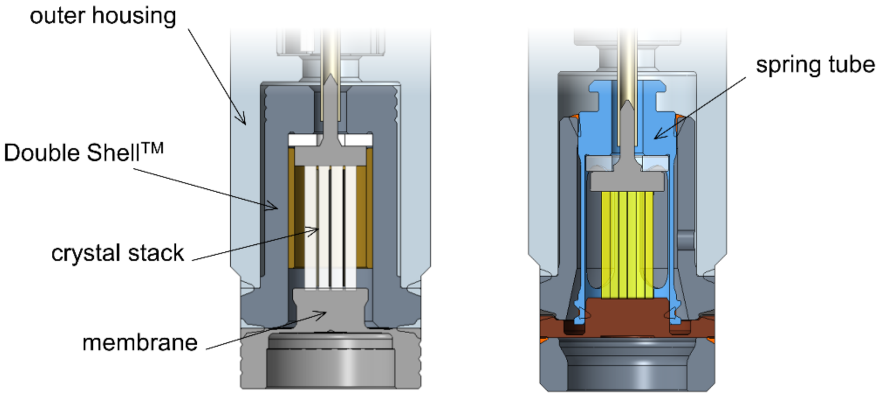

Figure 13: Left: Crystal stack of a pressure transducer with Double Shell^{TM} design to decouple crystal elements from external stresses. Right: Advanced design including an additional spring tube for improved robustness and performance.

A further improvement to the Double Shell^{TM} construction can be achieved by using a spring tube to achieve the necessary crystal stack preload (see Figure 13 right), rather than applying the preload directly via the membrane (see Figure 13 left). As the crystal stack preload is solely defined by the spring tube, the membrane can be further optimized without any need of applying the required preload. Briefly, the spring tube can be designed as a thin walled tube which can be fabricated for example by turning (see Figure 14A) or rolling and welding a thin metal sheet into a tubular shape (Figure 14B). Alternatively, the spring "tube" can be constructed of four individual laser-cut elements (see Figure 14C) which are arranged in a square providing an extremely tight packaging for further miniaturization. Moreover, having the preloaded crystal stack and spring tube forming an independent unit allows for more precise alignment of the individual transducer parts, meaning the cumulated tolerances can be further reduced and variations between individual sensors are minimized.

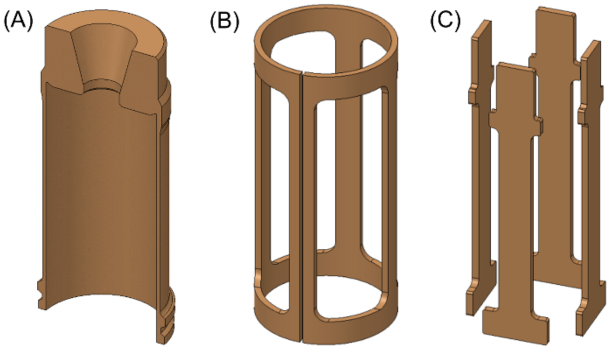

Figure 14: Various spring tube designs: A) solid tube spring fabricated by turning, B) rolled and welded tube based on a laser cut metal foil. C) four individual elements in square arrangement.

6.0 MULTIFUNCTIONAL TRANSDUCERS

While miniaturization is one option to save valuable space and weight, another option is to develop multifunctional sensors, meaning multiple physical quantities are detected within one transducer. In case of piezoelectric sensors, the detection of pressure and acceleration are closely connected. This circumstance can be exploited by designing sensors which are capable of providing individual pressure and acceleration signals. Piezoelectric crystals generate charges in response to deformation by external forces. The origin of the acting force or stress on the crystal can be caused by pressure or indirectly caused by accelerations. Unfortunately, the individual contributions to the signal cannot be easily distinguished.

An elegant method to properly compensate for the acceleration signal can be achieved by additional crystal elements within the transducer. While the original sensing elements are directly in contact with the sensor membrane and are thus susceptible to the external pressure changes as well as accelerations, a second isolated set of crystal elements is added. As these elements are well isolated from external mechanical stresses they are only sensitive to accelerations. With a careful design of these compensation elements they produce the correct amount of charge which is required to achieve an accurate acceleration compensation for the pressure signal. Considering the polarity of the crystal surfaces, the elements can be connected internally to achieve the acceleration compensation already within the transducer in order in minimize issues with signal interference (see Figure 15).

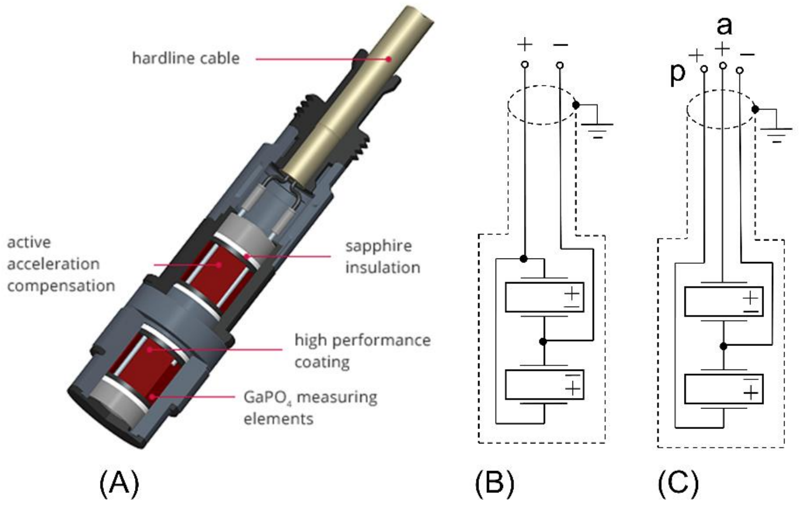

Figure 15: A) Pressure transducer with additional crystal elements for acceleration measurements. B) Concept of active acceleration compensation of the pressure signal using additional crystal element to improve signal reliability. C) Using separate outputs for the pressure signal (p) and acceleration signal (a) allows for simultaneous monitoring of accelerations without additional sensors.

While the possibility of acceleration compensation is already an important improvement, the acceleration signal itself carries valuable information for different applications such as bearing health and overall operation monitoring. Therefore, instead of internally wiring the acceleration signal, an additional output carrying the acceleration signal can be implemented. With this modification, it is possible to measure pressure and acceleration simultaneously using the same sensor. Thereby, valuable space is saved and errors due to different sensor locations are minimized if pressure and acceleration signals are to be correlated. Furthermore, installation and maintenance efforts are lower compared to using two separate sensors for pressure and acceleration. And lastly, in some occasions mounting space might simply be too restricted for two separate sensors, which would hinder simultaneous data collection. Obviously, the acceleration signal can still be used to compensate the pressure signal directly using analog summing or any kind of data evaluation tool after analog-digital-conversion.

7.0 CONCLUSION

In this work, several strategies to improve the reliability and usability of pressure sensors were presented, especially focused on high temperature environments as used for pulsation monitoring in gas turbine combustors. For ambient temperatures >500°C the available sensing technologies are mostly limited to piezoelectric transducers due to their unique temperature stability. Compared to piezoceramics the purity and high-temperature capability of single crystalline materials makes them the preferred choice for piezoelectric transducers. In addition to providing a superior signal-to-noise ratio, single crystalline sensing elements also lack pulse-noise events caused by ferroelectric depolarizations which lead to frequent signal dropouts. Especially single crystalline gallium phosphate ($GaPO_4$) is preferred because of its higher sensitivity, overall temperature stability (linearity) and lack of pyroelectricity (temperature cross-sensitivity) compared with the conventionally used quartz, tourmaline or ceramic materials. These properties allow for continuous pressure monitoring even in transient conditions such as during start-up or load changes of gas turbines and offer superior signal quality in the low-frequency region which is otherwise not accessible.

The importance of distinctive design principles regarding the crystal sensing elements and the mechanical design that fit best to the intended application were discussed. Miniaturization of pressure transducers gives more flexibility in choosing the best mounting spot and thereby inherently improving the signal quality. Moreover, multifunctional sensors allow for the measurement of pressure and acceleration using one combined transducer, thereby reducing the overall system complexity and maintenance requirements. Lastly, the use of laser vibrometers for direct measurements of the mechanical transducer properties and avoidance of adverse mechanical resonances was demonstrated. It highlighted clearly the importance of studying the complex interplay between transducer and cable assembly to guarantee highest signal reliability even during on-board use. Employing the strategies outlined in this work the reliability of high-temperature pressure monitoring as required for safe and stable combustion can be enhanced allowing for improved monitoring capabilities and increasing overall performance even under most challenging conditions.

8.0 TRANSITION SUMMARY

Current Exploitation Maturity Level (EML 0-6): 5
Current Technology Readiness Levels (TRL 2-9): 6
Target exploiter: Engine OEMs, Specific platforms
Exploitation type: Test cell only

Transition approach:
Gallium phosphate based pressure transducer (Piezocryst CP502, CP505, CP506) are well-established for pressure monitoring in heavy duty and aero-derivative gas turbines with ambient temperatures up to 700°C. Miniaturization of established technology as used in the Piezocryst CP5x1 transducer series is already used on stationary gas turbines and first test cell operations for validation on aero gas turbines with an engine OEM are planned in Q4 2018.

REFERENCES

[1] [G. Gautschi, Piezoelectric Sensors, Springer, 2002, doi.org/10.1007/978-3-662-04732-3_5

[2] P. Krempl, G. Schleinzer, W. Wallnöfer, Gallium phosphate, GaPO4: a new piezoelectric crystal material for high-temperature sensorics, Sensors and Actuators A: Physical, 1997, doi.org/10.1016/S0924-4247(97)80289-0.

[3] J. Rödel, W. Jo, K. T. Seifert, E. Anton, T. Granzow, D. Damjanovic, Perspective on the Development of Lead-free Piezoceramics, 2009, Journal of the American Ceramic Society, doi:10.1111/j.1551-2916.2009.03061.x

[4] C. Kittel, Introduction to Solid State Physics, Wiley, 2004, ISBN: 978-0471415268

[5] A. M. Hurst, T. R. Olsen, S. Goodman, J. VanDeWeert, T. Shang, Proceedings of ASME Turbo Expo, 2014, doi:10.1115/GT2014-27159

[6] P. Lutzmann, B. Göhler, C. A. Hill, F. D. M. van Putten, Laser vibration sensing at Fraunhofer IOSB: review and applications, Optical Engineering, 2016, doi.org/10.1117/1.OE.56.3.031215