High-temperature resistant pressure transducer for monitoring of gas turbine combustion stability

Fabrice Giuliani[y], Alexander Schricker[z], Andreas Lang[y], Thomas Leitgeb[y], Franz Heitmeir[y]
[y] TU Graz, [z] Piezocryst
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1 Abstract

The state-of-the-art concerning gas turbine combustors for propulsion and power is marked by the strong R&D effort over the two last decades on low-emission technologies and optimised system performance. Among the most promising low-NOx liquid-fueled injection technologies, we can cite the LP (P) (Lean Premixed (Pre-vaporised), operating pressure-ratio (OPR) ′10- 25), the PERM (Partial Evaporation & Rapid Mixing, OPR ′20-35), and the LDI (Lean Direct Injection, OPR ′30-60).

The well-known industrial problem that lies behind is the bridle of performance and danger for the combustor integrity due to combustion instabilities that can appear at such operating conditions, achieving critical levels of noise emission, vibration and heat release near the walls. Combustion instability is a multi-parametric problem, which involves a complex coupling between the system acoustic properties, the chamber flow dynamics and the instantaneous and local thermodynamic variables (Culick [1], Putnam and Dennis [2]).
If the combustor is shaped so that it performs stable combustion at the main operating points (passive control, with help of resonators for instance [3]), combustion may turn unstable during transients. This is critical on broad-operating-range systems. This aspect has encouraged the R&D on active control (see most of the works of A. Dowling at Cambridge University [4]), with successful applications on power gas turbine (note that the solutions presented in the papers [5, 6] respectively for Siemens and Alstom are specific to each system). Feasibility and certification of such control strategies remain an opened issue for propulsion systems.

One critical aspect of combustion monitoring is the sensing: a measurement technique placed onboard shall survey in real-time one significant parameter on combustion stability, here the unsteady pressure (in terms of dominant frequency and amplitude, for sound and pseudosound, see Hirschberg and Rienstra [7]), and this under aggressive conditions (high pressure ratio, high temperature, presence of a flame, vibration, corrosion, start and stop). This system shall be broad-operation range, have a long lifetime and reasonable drift. It shall also be small, robust, and easy to implement or to replace. In this work, we will present the results on the qualification of a high-temperature resistive fast-pressure sensor.

The company *Piezocryst Advanced Sensorics* develops and manufactures pressure sensors for individual applications in different industries. The transducers are based on the high-tech material $GaPO_4$ (Gallium phosphate crystal) and proven components that are all integrated and packaged.
The lately developed P-2 sensor, which is described into details in this study, is designed for monitoring combustion-driven pressure oscillations in gas turbines. The main property of GaPO4 is its ability to deliver a piezoelectric signal independently from the temperature (figure 1) on a broad operational range (some specifications of the P2 sensor follow: 0...200 bar, -70...560℃, 2Hz...50 kHz).

This $GaPO_4$ technology has been tested on the test rig for unsteady combustion analysis of the Institute for Thermal Turbomachinery and Machine Dynamics, at the Graz University of

Technology. This installation described in figure 2 amplifies the natural modes of a resonator placed upstream from a swirl stabilised air-methane flame with the help of a siren (Giuliani et al. [8]) in order to achieve realistic levels of pressure fluctuations within the combustor (up to 150dB).

A complete data set of basic experiments is presented into details (figure 3). The response of the sensor to specific operational conditions and the comparison with other measurement techniques are described. A discussion on the positioning, optimal distribution of several sensors and potential of these for control techniques conclude this paper.

The P-2 Pressure Transducer

The pressure transducer P-2 is designed to measure pressure fluctuations in combustors of gas turbines with excellent signal to noise ratio. It is based on the piezoelectric effect and can be used for dynamic and quasi static measurements. The sensing elements inside the Nimonic 90 housing are special shaped piezoelectric single crystals. Such crystals are insulators with non center-symmetric shaped unit cells. Under deformation, the charges in the lattice are separated; the remaining polarisation is a macroscopic effect which can be measured and converted into a voltage with an amplifier, operated in integrating mode. This also explains why static pressure cannot be measured realistically. The sensor, the cable and the charge amplifier, are electric components with a high but not infinite high electric insulation. Any charge that gets lost during the measurement changes the readout value. This effect is called electric signal drift. At high temperature the time constant for this drift is very dependent on the quality of the sensing element. Here, single crystal materials, like GaPO4, or Quartz have almost no impurities and hence are close to ideal insulators. These crystals are typically one decade better than natural materials and two decades better than ceramics.
Although the GaPO4 crystal was designed and researched just for the purpose to serve as the perfect crystal in piezo sensors, the stability and remarkably high internal resistance were also a bit fortunate. The material can be used at temperatures up to 900°C without loosing the piezoelectric effect. Quartz twins at approx. 350°C (depending on the acting pressure).

Some piezoelectric crystals and all piezo-ceramics have a dipole lattice structure, which is responsible for the pyroelectric behaviour. This tendency to deliver charges in the presence of thermal gradients is unwanted for pressure measurements because it cannot be separated from the pressure signal. The effect enters in the low frequent region of the spectrum and can be eliminated with high pass filters. Quartz and GaPO4 are not pyroelectric.

The rigidity of GaPO4 makes it possible to use sensing elements in transverse orientation. This still means that pressure is induced on two opposite surfaces, but the polarisation appears perpendicular to this direction. The size of the polarisation is dependent on the shape of the sensing elements and hence design-able. In comparison to a sensing element in the “traditional” longitudinal arrangement, such sensing elements are typically 5 times more sensitive.

The P-2 sensor is built up with three transversally arranged sensing elements. The mentioned high electric insulation can only be achieved with meticulous clean sensor parts and working environments. To ensure the very linear response to pressure, all surfaces in the line of force need to be flat and parallel to the submicron level. The sensors are assembled in clean rooms and sealed with electron beam welds at 10^-4mbar. The sensor is firmly connected to a mineral insulated cable which also withstands the operating temperature of the sensor. Still, due to the thermal dependence of the internal resistance of all insulators, the cable should be routed to colder regions on the shortest possible way.

For some application where pressure fluctuations are very low, but the system is exposed to vibrations, the signal from acceleration can exceed the pressure signal level. The acceleration signal of the sensor comes from the mass of the membrane and the sensing elements. It is like a pressure signal and cannot be eliminated with electronic after treatments. Therefore a twice as complicated version of the P-2, the P-6 has been built. This sensor incorporates essentially two sensors in the same confined space. The first sensor sees the pressure and the acceleration; the second sensor is arranged such, that it only sees the acceleration. The electrical signal from the second is subtracted from the first. Hence the vibrational noise is actively reduced by one decade. The remaining acceleration signal is dominated by triboelectric noise from the cable. Very often the small sensors that are exposed to vibrations are mounded to wing based turbines which tend to operate at higher temperatures. For this reason the P-6 sensor is designed for measurements up to 750℃.

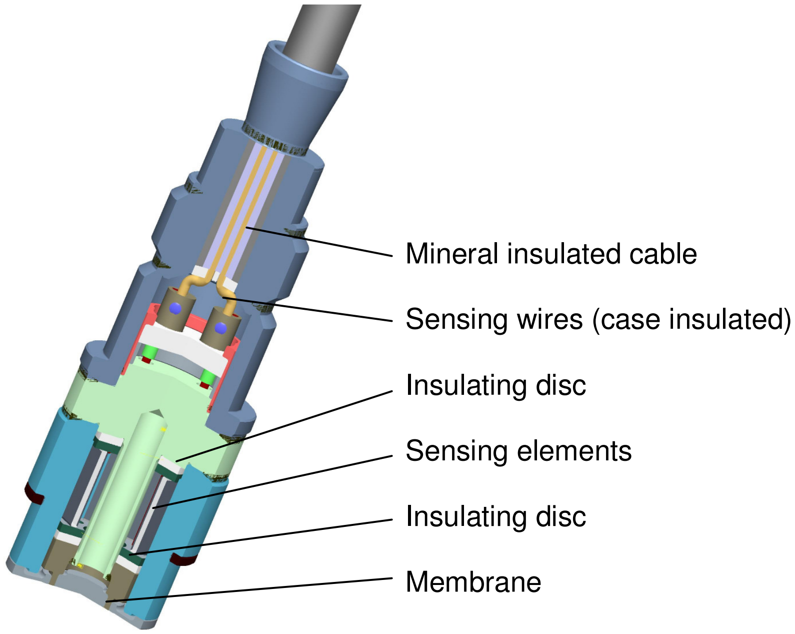

Figure: cut trough a P-2 sensor. The sensing elements are transversally arranged and electrically insulated from the sensor housing. All metal parts are made of Nimonic 90.

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