The Development and Introduction of High Temperature Optical Pressure Sensors in Gas Turbine Combustion Monitoring Applications

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Abstract— The increasing demands made on lower emissions, fuel and load flexible combustion systems continue to challenge engine architectures and instrumentation systems. Direct mount high temperature combustion stability sensors are needed, and these are being integrated into gas turbine control systems, to allow machines to reliably operate Dry Low Emissions (DLE) systems within progressively tightening standards. Some engine OEMs and customers wish to move away from waveguide (indirect) measurement systems.

I. INTRODUCTION

Oxsensis addressed this by applying Fabry-Perot optical interferometry techniques and creating robust, high temperature sensor structures which were linked with light management techniques and components from the optical telecommunications industry. This means that pressure-sensitive ceramic optical structures are non-electrically fibre-connected to an opto-electronics card and this arrangement replaces piezo-electric or piezo-resistive electrical instrumentation chains. Oxsensis managed the design and development to solve key technical risks including front end material selection and mechanical design, thermal shock, vibration sensitivity, process design, and opto-electronic systems integration. Oxsensis has demonstrated progress in Optical pressure sensing in gas turbine applications including the direct benefits of close coupled sensors in lieu of remote sensing using sensing lines or 'waveguides' [1].

Progressive steps were taken over 10 years to prove system elements on combustion and gas turbine rigs, across the manufacturer and research gas turbine sector, and the system was integrated in a multi-channel system and then in a single channel product, working with Centrax Gas Turbines (UK) and applying the instrumentation to the CX-A05 3.5 and 5.5MW DLE gas turbine products.

The product application work included detailed requirements and interface definition, followed by test validation. This was supported by a UK DECC (Department of Energy and Climate Change) grant.

Figure 1. Centrax CX 501-A05 Core Engine

In service in the Centrax test cells for engine overhaul test, and in field deployed units since 2016.

The initial industrial gas turbine product deployment has demonstrated reliable field operation of this technology and the single-channel product configuration on a 3-7MW gas turbine range shows that scaling to multi-channel and larger gas turbines is attractive.

In parallel, aero-engine flight applications are being addressed, with Oxsensis partner Parker Aerospace and this involves additional challenges including the environmental conditions of the opto-electronics module, and the adaptation of components, processes, software, and systems to aerospace standards. The path to flight product has similarities to the land-based gas turbine adoption in that it involves staged risk reduction via component test, sub assembly test and systems qualification – although the required resources and timescales are increased.

Further industrial multi-channel applications are being configured, with OEM and service provider assistance. These also involve higher engine cycle conditions, meaning temperature and pressure in particular, and can also involve changes in routing, installation, and systems interface. This extends the engineering activity, with a greater emphasis on test validation and qualification for applications.

Beyond dynamic pressure measurement systems, multi-measurand operation has been demonstrated, in which static pressure and sensor temperature is also recorded. Aligned with direct mount casing or fuel injector mounted sensors, this could significantly enhance the ability to detect can-by-can performance or anomalies.

II. Design and Principle of Operation

The instrumentation system is based on a micromachined sapphire sensing element schematically shown in Figure 2. The whole sensor system consists of an optical sensor (head and flexible lead-out), optical cable connecting the sensor, interrogator unit, and the interrogator unit which converts the optical signal into an electrical signal in a form that is required to interface with the customers data protocol.

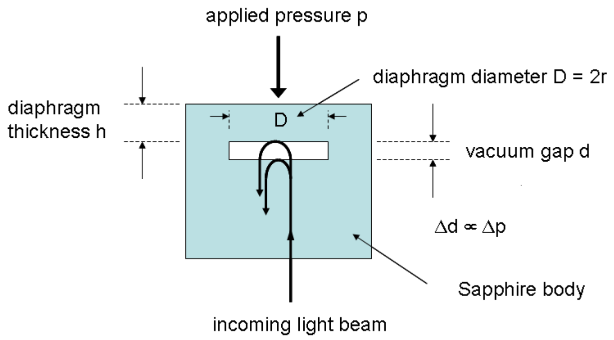

Figure 2: Optical sensing element

The sensor head is illuminated with broadband light and the returned signal, caused by partial reflections occurring at each optical interface, is filtered and measured using photodetectors. The design of the optical system is such that the pressure sensing cavity response can be isolated effectively. Applied pressure deflects the diaphragm that changes the length of the optical cavity and the design of the sensing element is such that the deflection of the diaphragm is proportional to the applied pressure, across the operating temperature range of the sensor.

The use of sapphire as the sensing structure allows its high temperature capability to be designed into a harsh environment sensor head. Sapphire has a melting point > 2000°C and material properties maintained to at least 1300°C.

The optical interrogation unit comprises a broadband light source, optical coupler and light delivery to/from the fibre mounted sensor head and then the returned light is passed through a filter stage and then to photodetectors which address two wavelengths of returned light. Figure 3 shows the interrogation scheme.

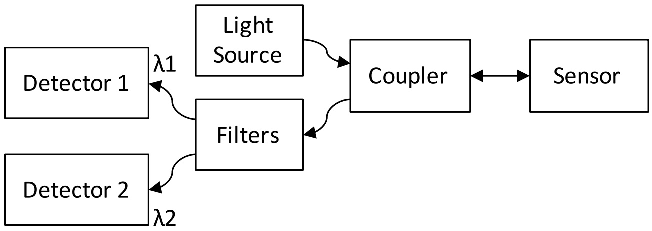

Figure 3: Interrogator block diagram

A linear response is achieved by applying signal processing to the photodetector signals, as shown in Figure 4. The use of two wavelengths makes the system insensitive to any intensity fluctuations due to losses in the fibre coupling the interrogator to the sensor.

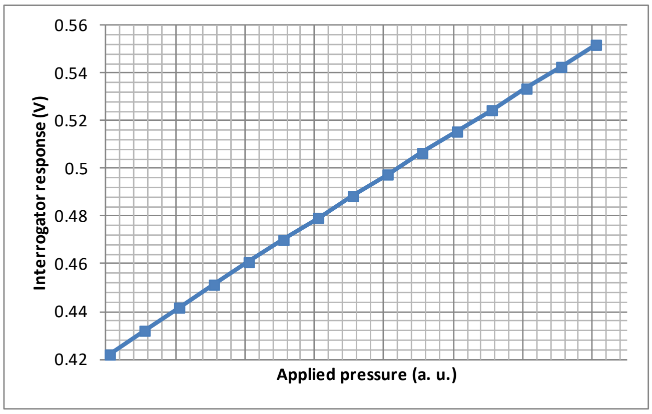

Figure 4: Interrogator response to applied pressure

The core instrumentation system has been packaged to be suitable for application to high temperature gas turbine casing locations, and in some applications has been adapted to be suitable for integration into fuel injector structures. The essential point of this work has been to move previously indirect or 'waveguide' applications to close coupled direct mount applications. For the sensor assembly, this comprises a superalloy sensor head casing, which carries the sapphire sensing element and includes sealing, reinforced flexible lead out and fibre strain relief system and a connection to a low-cost patch cord which couples the transducer to the interrogator. The sensor head mounting location on modern gas turbines has to address front face gas temperatures of up to 800-1000 °C and then metal casing mounting conditions in the 650°C – 750 °C typically. The sensor conduit routing then typically follows the engine casing and transitions within the gas turbine enclosure to the interconnection lead (optical in this case). The 'direct' mount sensors, compared to 'waveguide' mounted sensors, operate with higher sensitivity and a wider acoustic bandwidth, as reported previously by Oxsensis [1], and as shown in Figure 5 below.

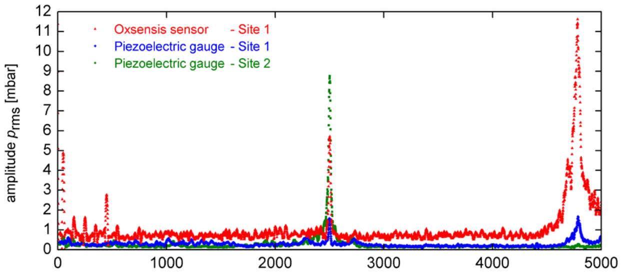

Figure 5: Oxsensis and DLR test results ref [1]

Figure 6: Optical instrumentation system

The optical interrogator is packaged and developed to suit the control cabinet/control room environmental specifications for the land-based power generation customers who are initially using this technology. Figure 6 shows the overall system including the single channel DIN rail mounted optical interrogator. The main design constraints for land-based applications are the storage and the start-up environmental requirements – in contrast with flight applications which also include engine vibration tolerance and wider extremes of temperature. The core optical systems address both requirements.

III. Introduction to Service

Oxsensis instrumentation systems have been used since 2014 by Centrax Gas Turbines, UK, for engine test bed instrumentation including pass-off production testing. Units have also been deployed since 2016 on Centrax KB5 and KB7 DLE units in field installations to monitor units. This early adaptation of Oxsensis optical technology to in-field product use was accelerated by grant support from the UK Department of Energy and Climate Change (DECC).

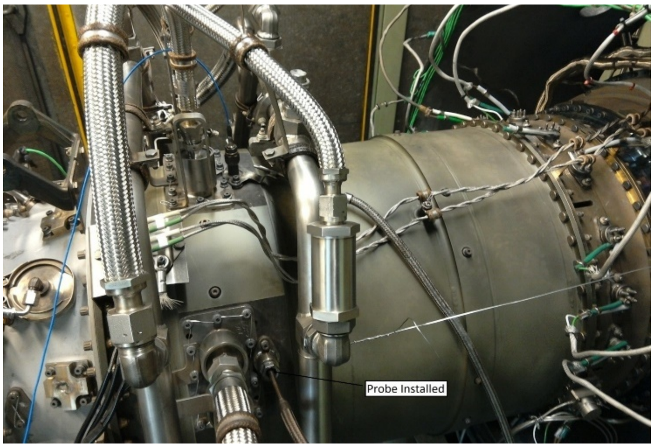

Figure 7: Optical pressure sensor fitted to Centrax CX-A05 DLE Gas Turbine

The use of the technology on engine re-build test bed measurement applications was useful to gain experience from a high number of fit/re-fit operations and also a high ratio of starts to hours run. This complements the infield fired hours experience.

In parallel with this work, using 15 bara pressure range sensors, Oxsensis has applied the system to higher pressure ratio, larger gas turbines and as part of this work has added Design Assurance Testing (DAT) programmes to match the extended pressure and temperature environmental requirements. For very large gas turbine units there is a requirement to extend the high temperature flexible conduit length to accommodate casing mounted routing of the sensor and more of the sensor structure is exposed to high vibration levels. The DAT testing in 2018 and 2019 is extending the qualification testing and endurance testing experience of this product family. The DAT programme includes vibration, temperature cycling, pressure cycling, and chemical resistance testing, as well as confirmation test operations on new engine types to validate performance against known, legacy or prior instrumentation systems. This work extends Oxsensis coverage to additional OEMs.

IV. Results

Optical pressure sensors have been deployed as production systems on Centrax CX-A05 3.5 and 5.5MW gas turbines since 2016 and are in use on rebuild engine test beds at Centrax's Newton Abbott facility. These systems provide casing mounted direct pressure measurement monitoring on DLE fielded units across Europe. In-service performance has matched measurement requirements for combustion pressure variations. The opto-electronic interrogation units have been successfully interfaced with the Centrax control system, which is based on modern programmable logic controller interface modules and in many cases also provides a remote monitoring facility for Centrax customers.

In service and installation issues have been encountered and addressed, helping Oxsensis to refine the product and these have included producing training material for optical connector cleaning, and detailed mounting and routing of the sensor assembly. Additional gas turbine applications have generated assembly variants which may also prove applicable to Centrax unit deployment, e.g. in terms of connectors and patch cord connections.

V. Next steps

The systems described here will be applied to larger gas turbine units, operating at higher pressures and higher casing and gas stream temperatures than on the 3.5-5.5MW range of aero derived gas turbines described in this paper.

The systems will be applied to multi-channel combustion monitoring systems and can be linked with data analysis and monitoring systems. Multi-measurand systems have been demonstrated and reported by Oxsensis [2]. These provide a natural extension to combustion dynamics monitoring and control; using sensor self-temperature measurement to enable static pressure and boundary layer temperature to be measured in addition to dynamic pressure.

In partnership with Parker Aerospace, Oxsensis is also offering flight gas turbine Engine Pressure Measurement (EPM) systems and these use a variation on the described interrogation scheme, as well as addressing the component qualification requirements for aero engine mounted electronics, software, and system qualification. The land based gas turbine combustion monitoring product development and deployment is therefore enabling a parallel flight engine path to develop. Oxsensis has AS9100D Quality Management System accreditation as part of its Aerospace supply chain credentials.

VI. Conclusion

Oxsensis has developed, matured, and delivered into commercial service, a family of optical pressure sensors for use in turbomachinery applications. Early customers have helped Oxsensis to tailor its designs and service delivery to suit industrial power generation requirements. This work is extending to other OEMs and to higher pressure/higher temperature gas turbine applications. In parallel, and in partnership with Parker Aerospace, Oxsensis is offering flight engine optical pressure sensor systems, and this involves further development and qualification work for engine mounted opto-electronic systems.

Acknowledgment

Oxsensis would like to thank Centrax Gas Turbines Ltd for their support and collaboration in applying this system to their 3.5-5.5MW gas turbine range.

The support of the UK Department of Energy and Climate Change is gratefully acknowledged in assisting with industrialisation of the technology.

Oxsensis partner Parker Aerospace is instrumental in extending the reach of this core technology to flight gas turbine propulsion systems [3].

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