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Enabling the Extraordinary
To Fly To Power To Live

OPTICAL MEASUREMENTS
FOR CONDITION MONITORING

Gianluca Nicchiotti

Presentation Outline

The Green Push

Lean Combustion

Hydrogen

Optical Sensing

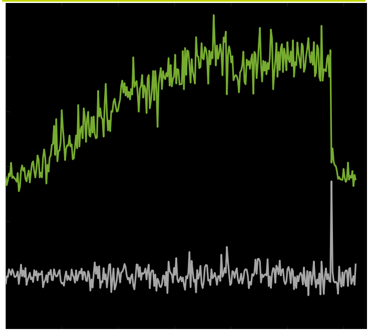
Fabry-Pérot Working Principle

Benefits

Meggitt Sensor

System Architecture

Properties and Features



Optical vs Piezo

Test Campaign

Results

Conclusions

Current developments

Take away concepts

Questions

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THE GREEN PUSH

Green Push and Sensing Technologies

End User

- Zero Carbon Emission

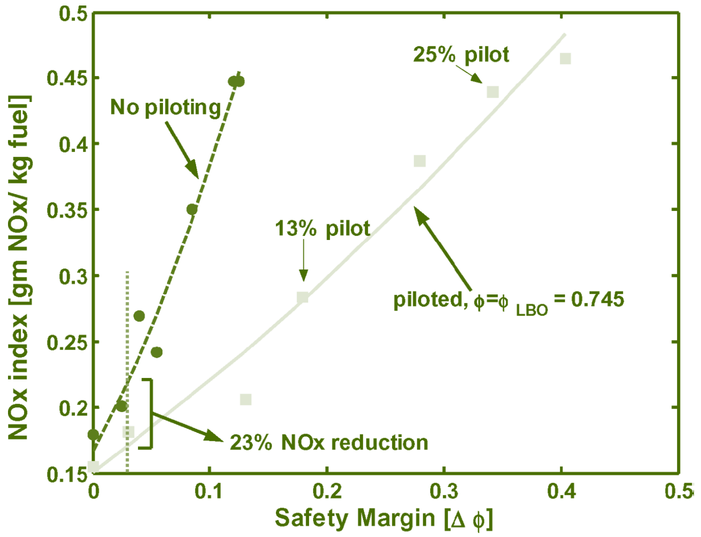
Customer

- Lean Combustion (Reduce LBO Safety Margins)
- New Fuels: Hydrogen

Sensing Technology

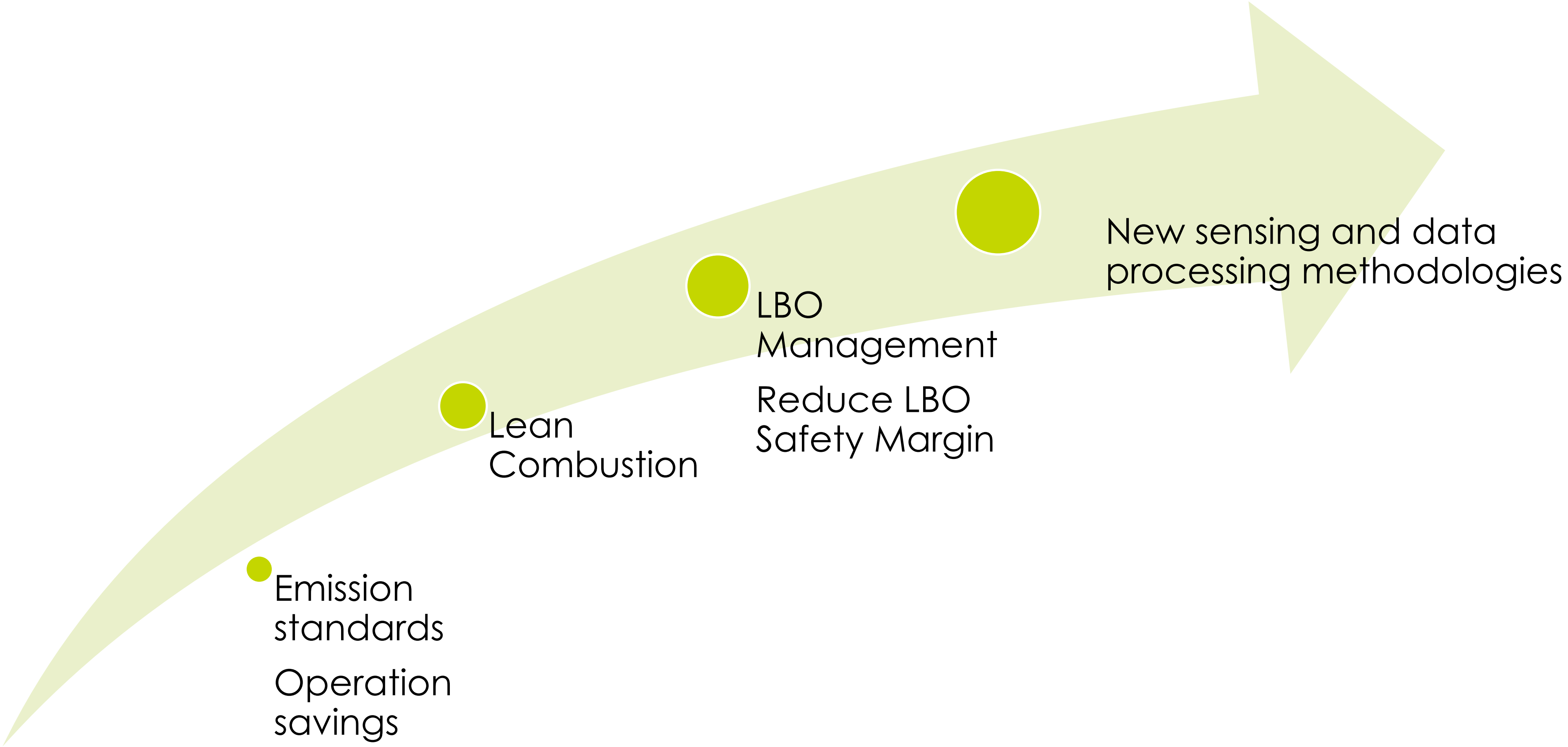
- Flame Monitoring
- Lean Blow Out(LBO) detection/prediction
- FlashBack detection/prediction

Source Georgia Tech



Way1: Lean Combustion

Motivation and Consequences



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Lean combustion challenges

Higher reactant flow velocity

Reaction time not keeping the pace of mixing time

Pulsations due to flame-front instability

Consequences

- Lean Blow Out
- Flame instabilities

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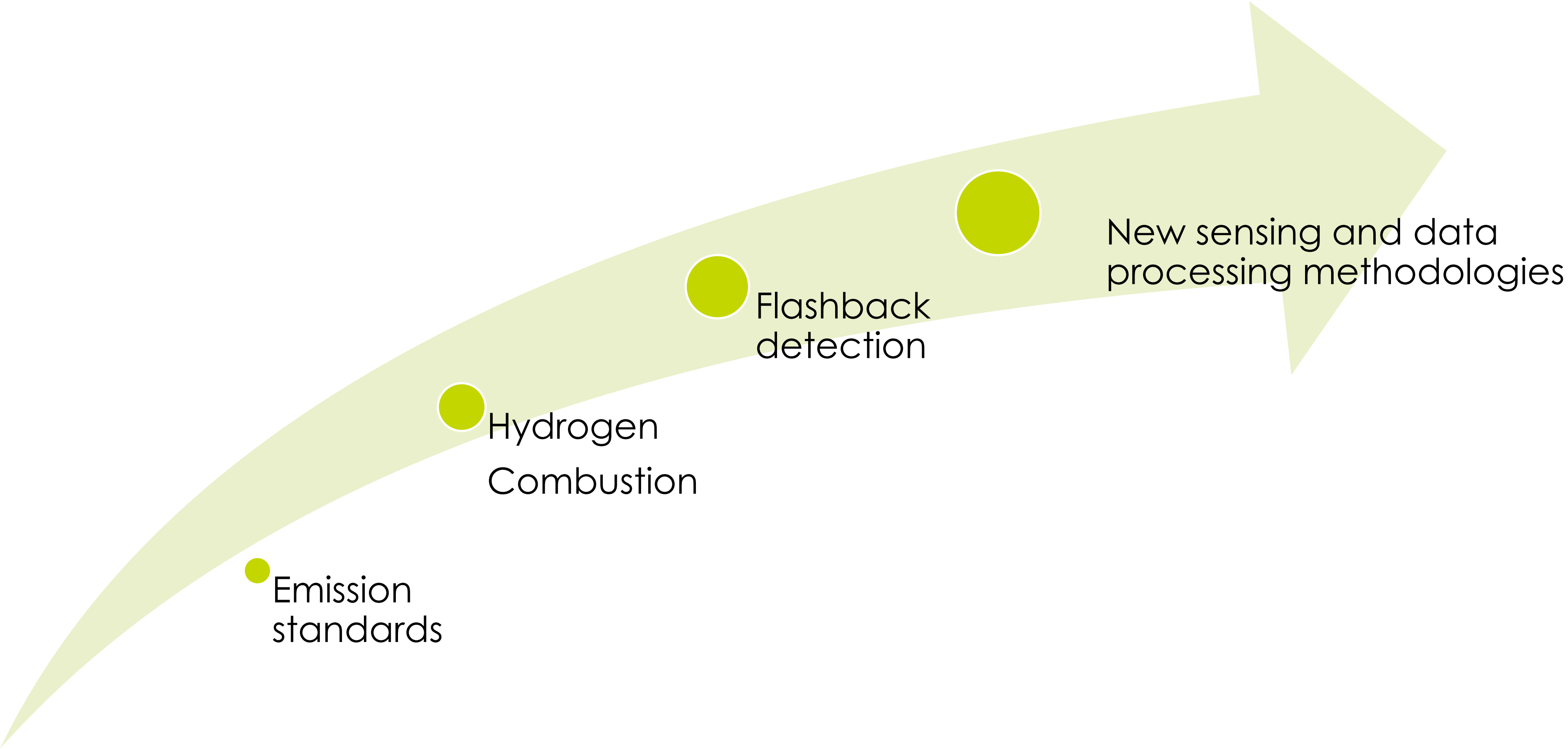
Way2 :Hydrogen

Motivation and Consequences



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Hydrogen combustion challenges

Higher flame velocity

Thermo-acoustic effect : hydrogen addition is likely to favor high-frequency instabilities

Change in flame color from visible to IR: at **100% hydrogen the flame is invisible to the eye**

Consequences

- Flashback
- Flame instabilities
- Flame detection

Sensing Technologies

Rationale Capability and Drawbacks

Burning velocity, flame thickness and flow dynamics govern flame processes close to LBO and Flashback producing corresponding changes in:

- Ion Emissions
- Flow speed
- Flame Shape
- Pressure/temperature

Chemiluminescence Detector

Maintainability

Presence and strength of the combustion process
Reaction rate and heat release rate

Particle Image Velocimetry (PIV)

Operating temperature

- Quantitative flow visualization technique
  Instantaneous whole-field fluid velocities

High-speed intensified CCD camera

Response Time

- Flame presence and shape Piezo-Electric

Dynamic Pressure Sensors

SNR at high temperatures and low frequencies

- Temporal rate of change of heat release

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Optical Sensors & Green Challenge

Challenge	Green Combustion	Conventional Sensors	Optical
Temperature	Combustion temperatures↑	Temperature limitations more severe	All passive head – more headroom upwards
Reliability	Higher temperature requirement	Active (piezo-electric/resistive)	All passive head – higher reliability expected
Sensitivity	Maintain at higher temp	↓ with ↑ temperature	Constant with ↑ temperature
Bandwidth	Thermo-acoustic oscillation BW ↑	Semi-infinite tube limits BW	Direct mounting
Flame Health Monitoring	Flash Back Blow out phenomena	LowFrequency limitiations	Immune to twinning pyroelectricity
Noise	More complex control systems	Electrical cabling/shielding	No EMI on fibre link/sensor

OPTICAL SENSING

Meggitt Positioning

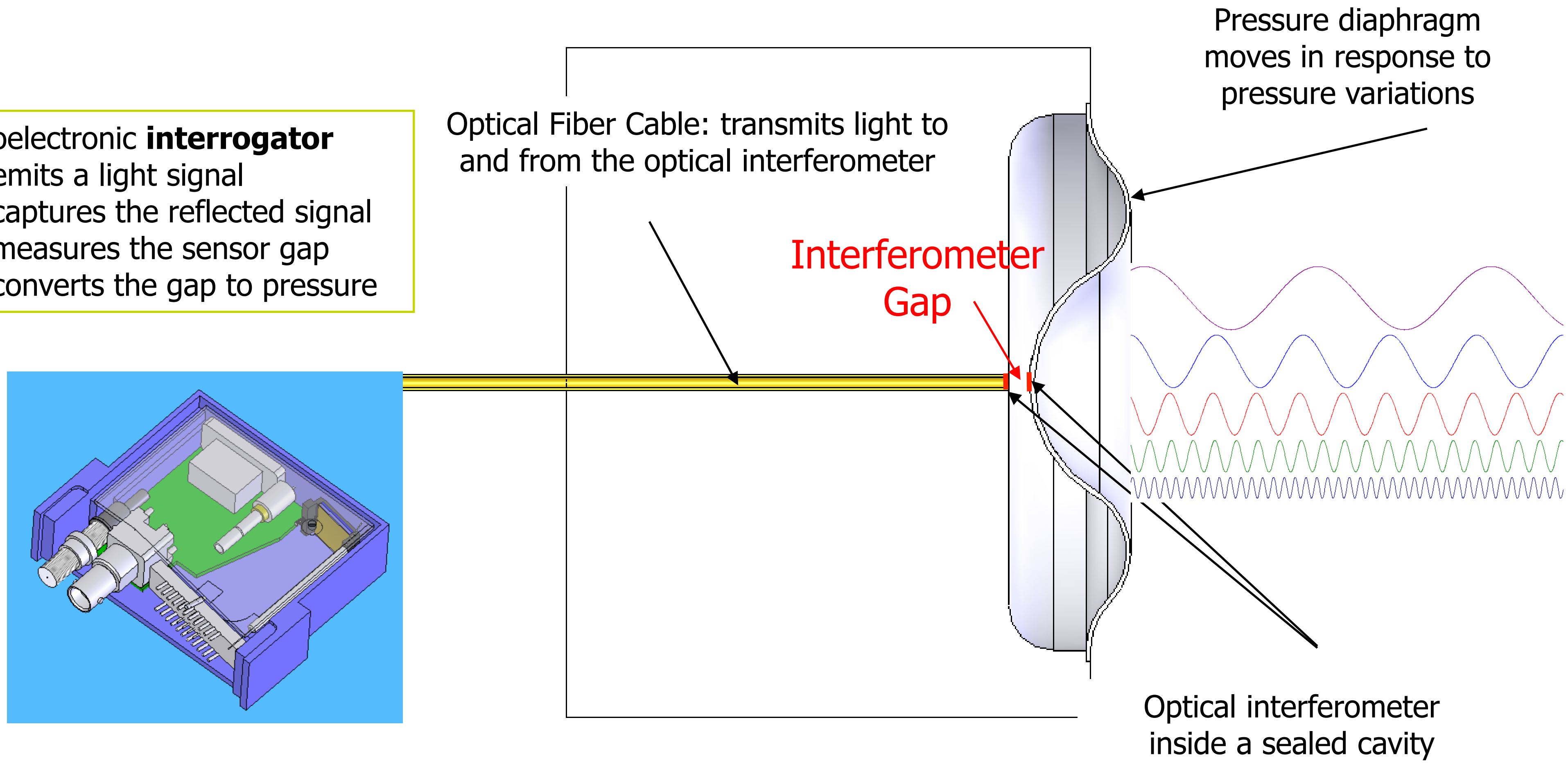
- Meggitt's view on optical sensing technologies trend
  - Commercially widely deployed in Medical and O&G
  - On-going transition from advanced research stage to implementation on in-service asset in Aerospace and Power Generation
  - Current base of technology providers is predominantly SMEs
- Meggitt's strategic positioning
  - Become a world-class integrator of optical sensing technologies for Aerospace and Power Generation
- Already active partnerships and projects
  - Point sensing (Fabry-Pérot): Pressure, vibration, temperature sensing, …
  - Distributed sensing (Fiber Bragg Gratings): Embedded optical fibres to measure strain and temperature

Fabry-Pérot Point Sensing

Working principle

Optoelectronic **interrogator**

- emits a light signal
- captures the reflected signal
- measures the sensor gap
- converts the gap to pressure



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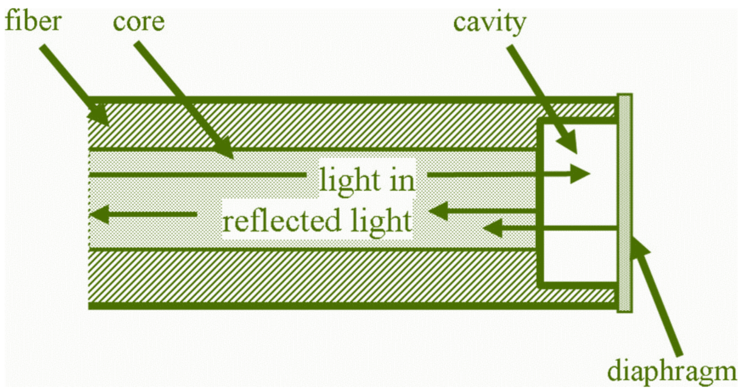
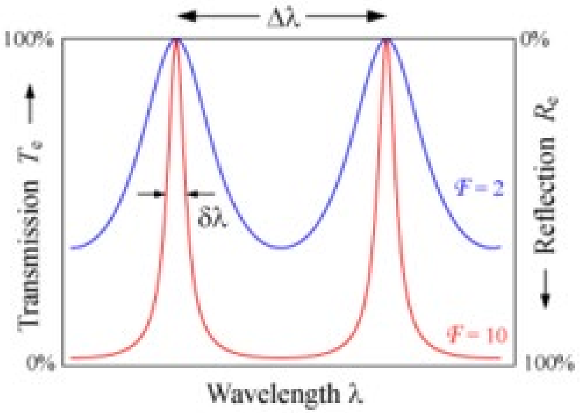
Fabry-Pérot Point Sensing

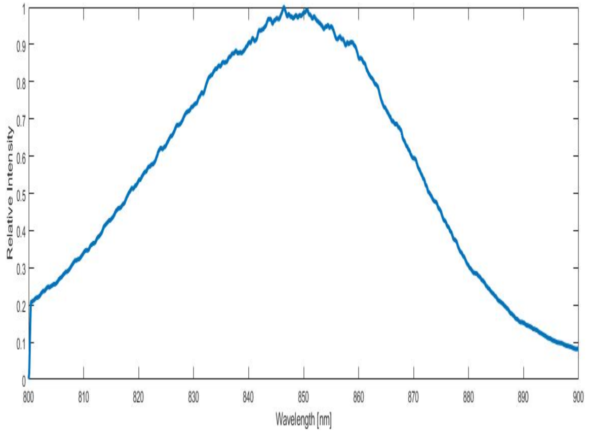
Interferometer Characteristics



- **Low Finesse i.e., low mirrors reflectivity**



- **Wideband light source (50 nm FWHM)**



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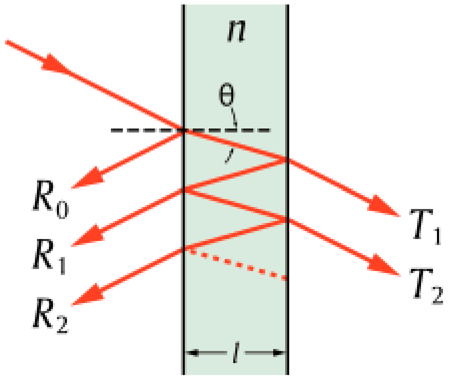
Fabry-Pérot Point Sensing

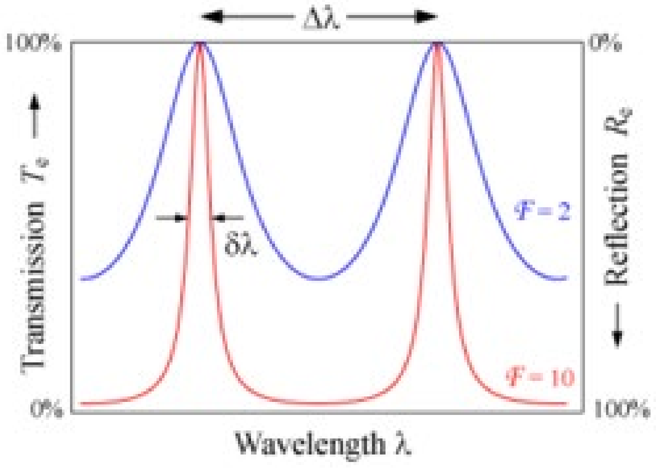
Interferometer: Basic Description



- Fabry–Pérot interferometer is a cavity made by two parallel reflecting surfaces. The reflected light is frequency modulated as a function of the cavity size.

- The spectral response of a Fabry-Pérot is determined by interference between the light reflected from different surfaces

- At every reflection phase increases of $\delta = \left(\frac{2\pi}{\lambda}\right) 2nl\cos(\theta)$



- Reflection coefficient is $R(\lambda) = \dfrac{F\sin^2(\frac{\delta}{2})}{1 + F\sin^2(\frac{\delta}{2})}$

- Where F is the finesse $F = \dfrac{4r}{(1-r)^2}$

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Meggitt Optical Sensing Technology

Optical Technology : Benefits

- Enhanced sensitivity & accuracy
- Better sensitivity @ high & low frequencies
- Insensitive to EMI perturbations
- Inherently safe
- Extremely compact size (sensor head)
- Suitable for multiplexing
- Multiple sensing capabilities (pressure, temperature, strain,…)

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Fabry-Pérot Point Sensing

Versatility

- The dimension of the Fabry-Perot gap modulates the reflected spectrum

- The measured spectrum contains the information of the gap dimension =>

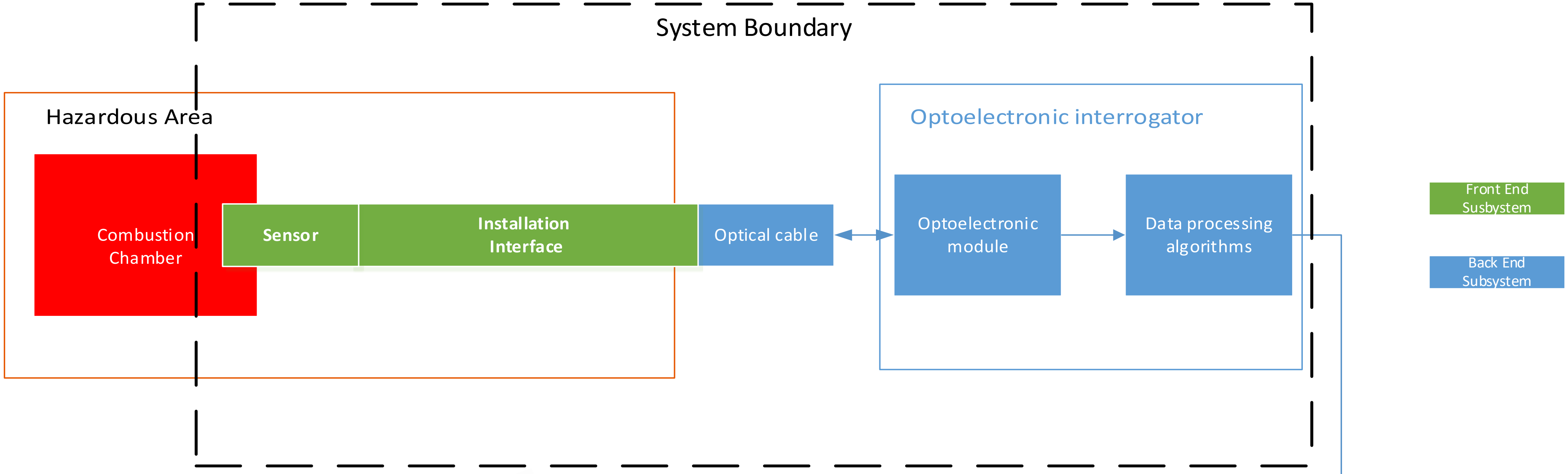
  Any physical quantity modifying the FP cavity dimension can be related to the reflected spectrum

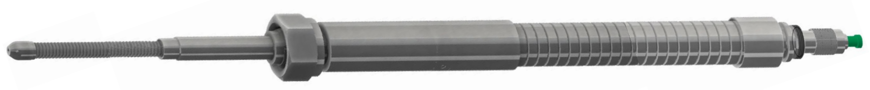
- Different cavity or processing designs allow to measure either:
  - “Dynamic” Pressure
  - Static Pressure
  - Temperature
  - Displacement , Vibration, etc.

MEGGITT SENSOR

Optical Sensing System

System Architecture





Sensor

Interrogator

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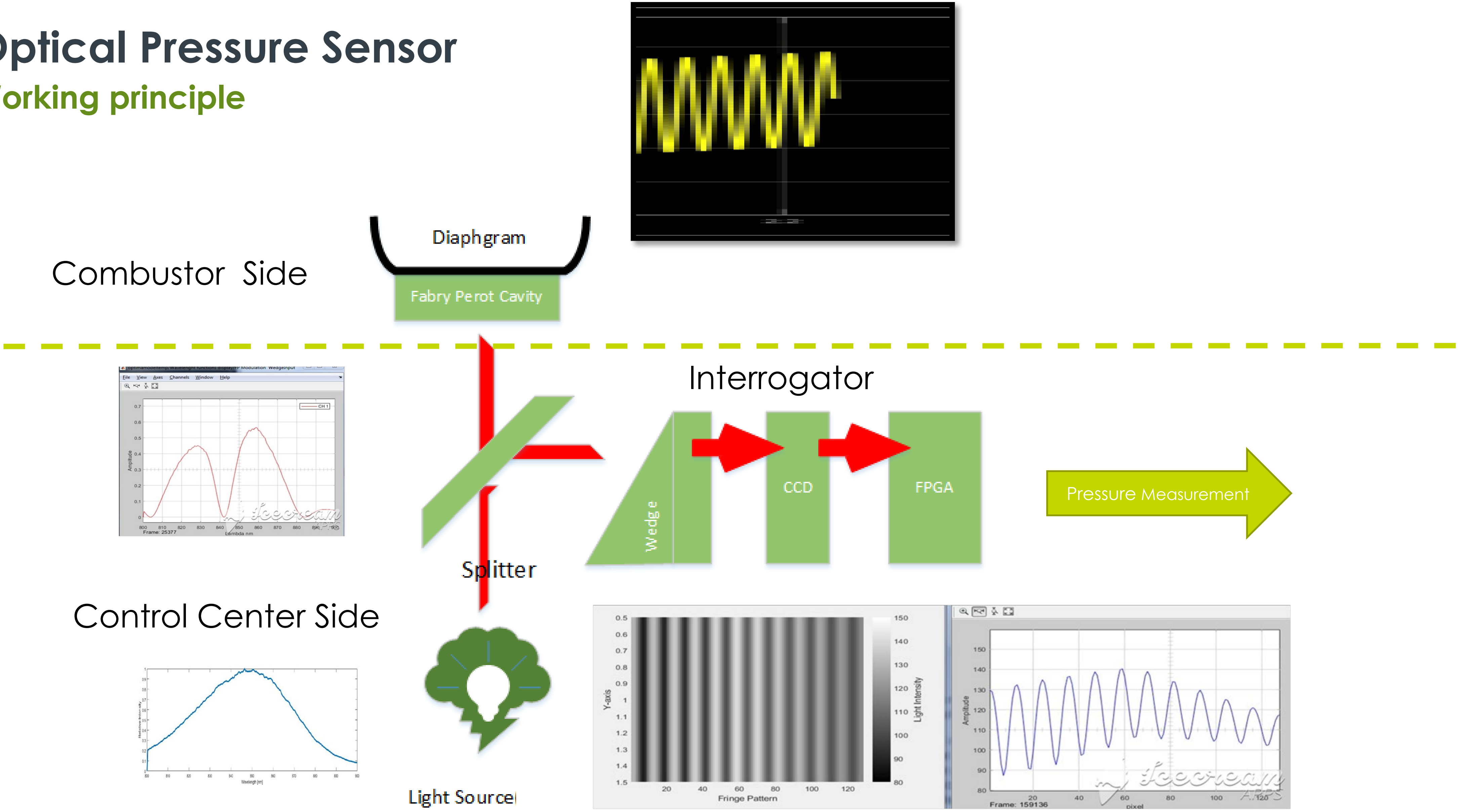
Optical Pressure Sensor

Working principle



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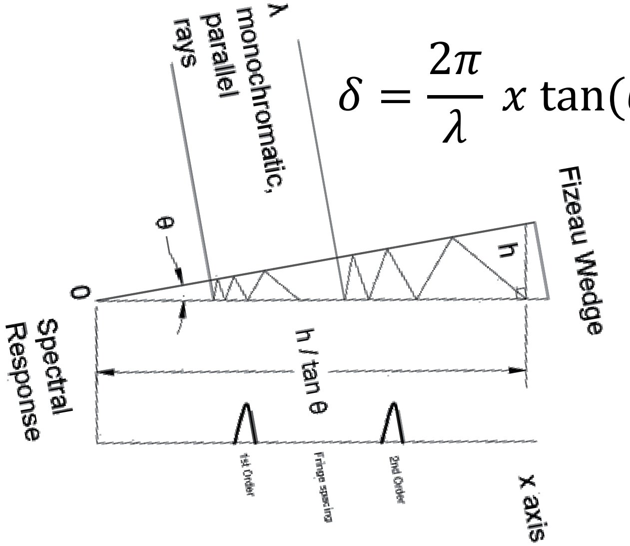
Fabry-Pérot Point Sensing

The Fizeau Wedge Role

$$\delta = \frac{2\pi}{\lambda} x \tan(\theta)$$



Wedge

- Fizeau wedge consists of two surfaces intersecting at a very small angle
- Transmitted light peaks occur $T(\lambda) = \dfrac{1}{1 + F\sin^2(\delta)}$

Process

When the thickness of the FP gap changes with diaphgram deflection, the peak the location of maximally transmitted light will shift a corresponding amount to a new position along the fizeau wedge

CCD

- The CCD array placed behind the Fizeau wedge receives the spatially spread light signal At each pixel corresponds a unique Fabry Perot gap thickness

Fizeau wedge converts a spectral modulation into a spatial modulation

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Optical Components

Key equations

Fabry-Pérot Reflectivity

$$R(\lambda) = \frac{F\sin^2(\frac{\delta}{2})}{1+F\sin^2(\frac{\delta}{2})}$$

Wedge Transmissivity

$$T(\lambda) = \frac{1}{1+F\sin^2(\delta)}$$

Optical Pressure Sensor

Design goals and main features

Improve piezo performances:

- Better SNR for frequencies lower than 50 Hz at high temperature
- Insensitivity to vibrations
- Insensitivity to EMI

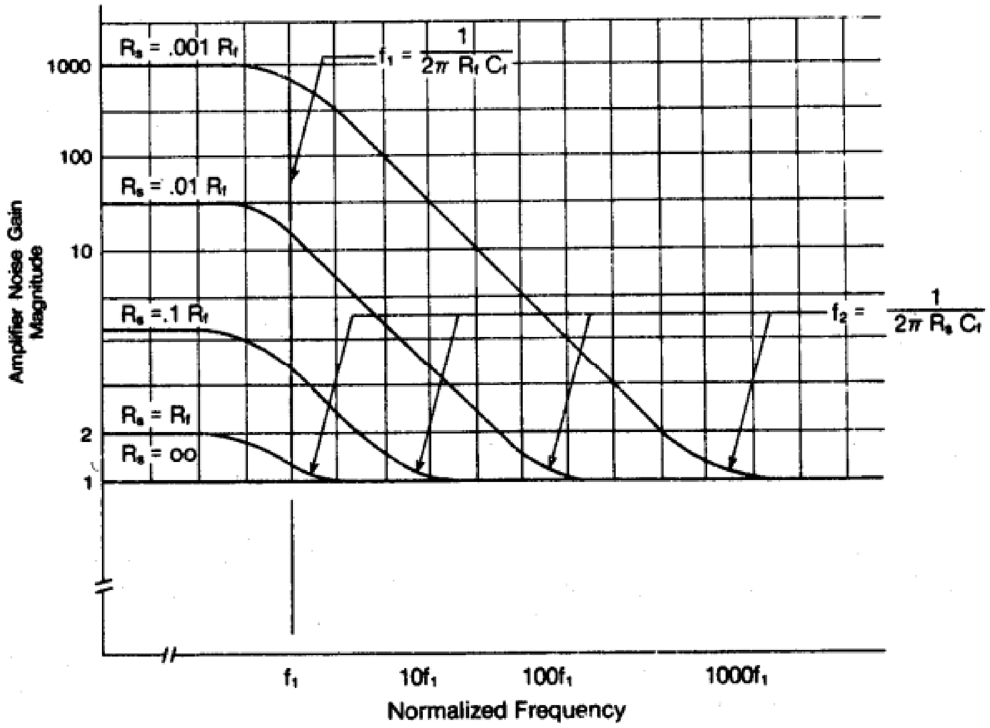
Parameter	Feature
Dynamic pressure range Full Scale	0.2 to 3 bar pk-pk
Frequency response	2 to 20000 Hz
Precision	0.2 mbar pk
Accuracy	< ±7%
Operating temp. range	-55°C to 600°C (survival 650°C)
Operating pressure range	to 30 bar (survival 69 bar)

OPTICAL VS PIEZO

Piezoelectric sensors

Low frequency response limitations

Increase of temperature causes the rapid drop of sensor resistance (x10 per each 100°C) that significantly increases the noise levels that may masks the low amplitude pressure changes at the low frequencies



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Test Campaign

Objective

Compare the optical system with its piezo counterpart

within several realistic scenarios representative of gas turbine combustion

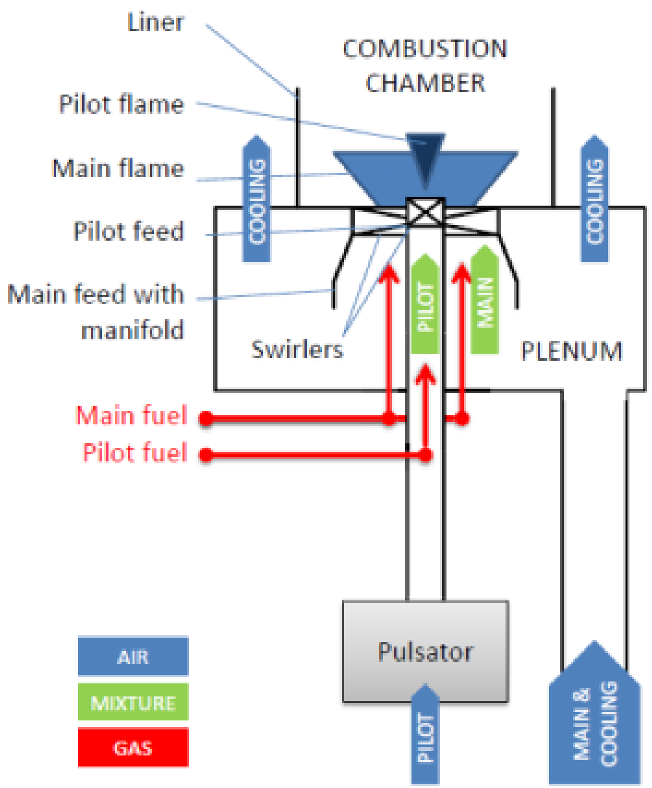
in a controlled, precise and repeatable manner

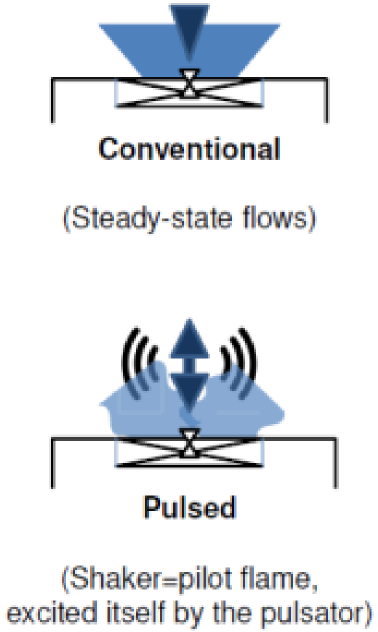
Focus on

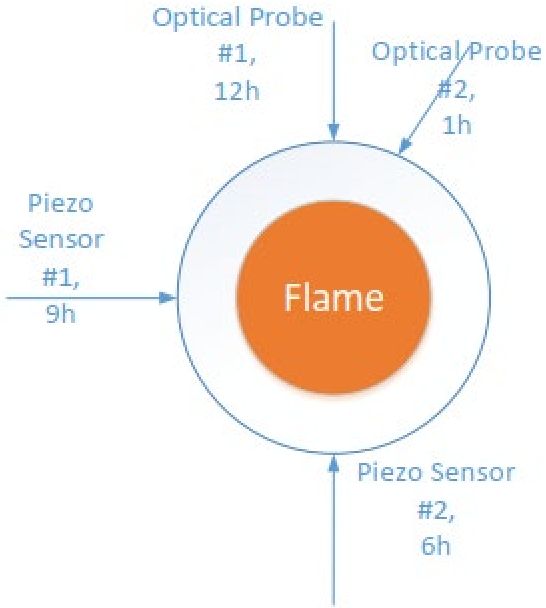
- Vibration perturbation Electromagnetic Interference
- Capability to detect combustion instabilities
- Combustion event detection
  - Ignition
  - Flash-back
  - Change in regime
  - LBO

Test Setup

Test rig scheme and sensor arrangement







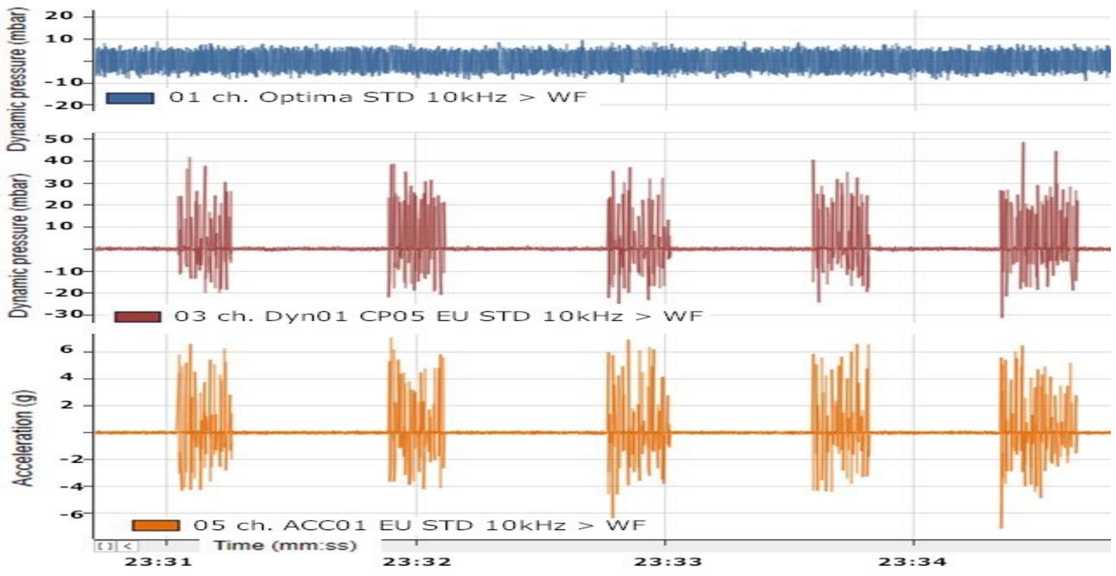
Test Campaign

Hot flow experiments

Test	Method	Analysis
Ignition EMI	Spark ignition with and without gas	Coherence with accelerometer
FlashBack	Main air cooling air ratio	Pressure low bands
Premixed to Diffusion Flame	Varying burning air	Coherence Chemiluminescence
Combustion instabilities	Koelner Dom	Check amplitude and phase at eigenfrequencies
Imminent LBO	Increase mass flow	Time/frequency domain

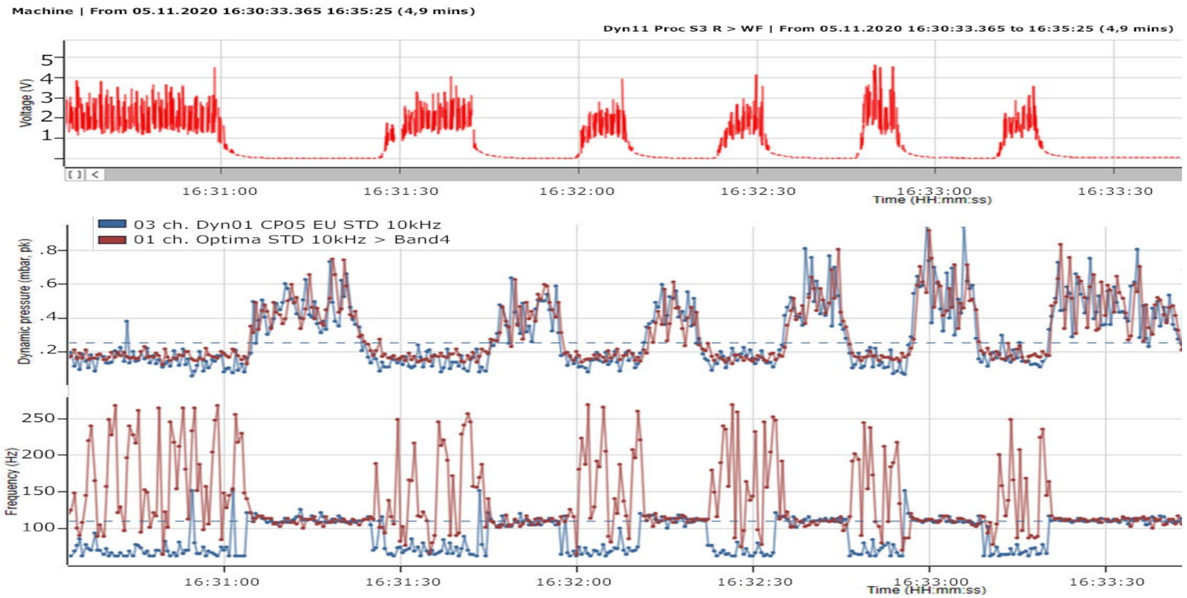
Test Campaign

Results I



Ignition EMI

At ignition, the optical probes are much less disturbed by EMI than the piezoelectric transducers and accelerometers



Premixed/diffusion transition

Both measurement principles qualify for the detection of diffusion flame matching the chemiluminescence method

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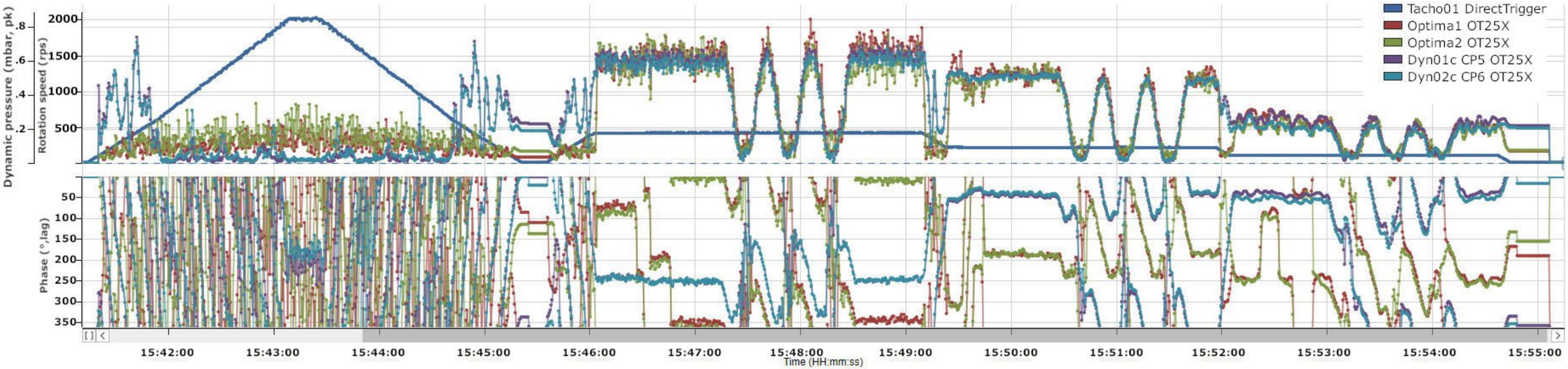
Test Campaign

Results II

Combustion instabilities

The optical sensor and piezoelectric sensors show a good agreement in amplitude and phase response



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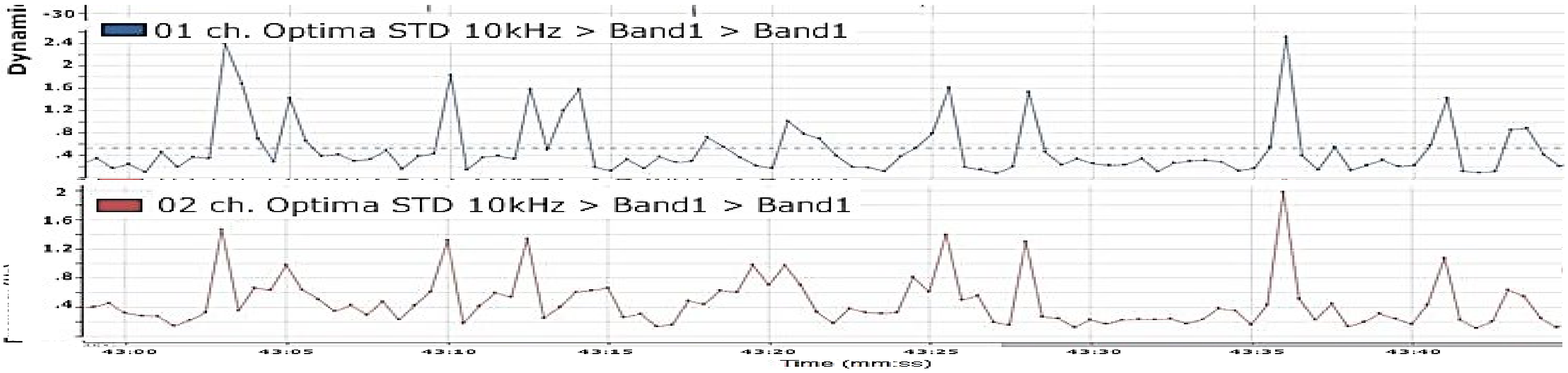
Test Campaign

Results III



Flashback

- In the low frequency band of the optical probes [2-5 Hz], the double-peak structure at each cycle coincides at fixed frequency with the flashback events.
- This analysis cannot be performed with piezo and provides a more reliable (and physically meaningful) flashback detection.
- The low frequency band analysis may help to identify flashback precursors

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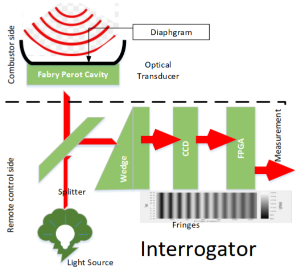
Test Campaign

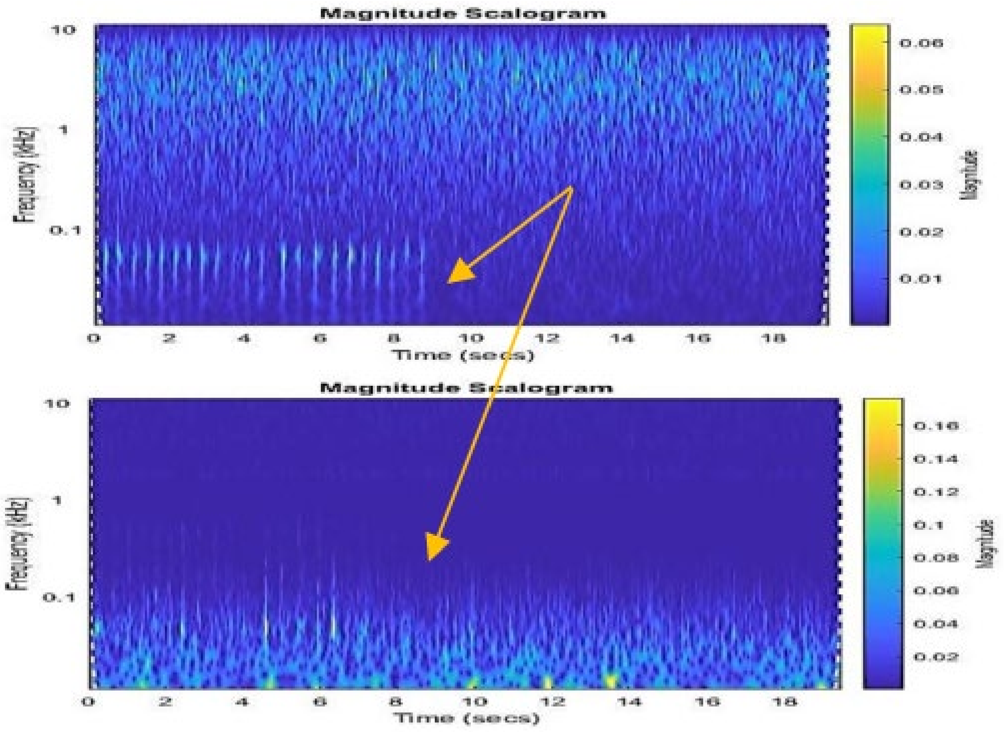
Results IV: LBO and Low frequency characteristic

Scalograms in proximity of the LBO event for both the optical (top) and piezo-electric (bottom) sensors; arrows indicate the LBO time event at t = 9s

Optical



Piezo-electric

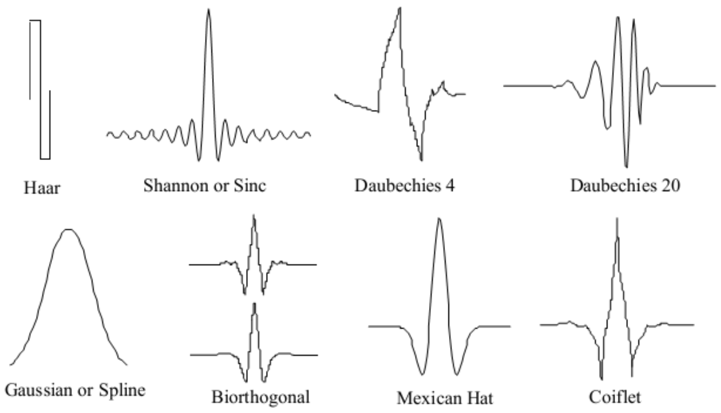


Optical sensing

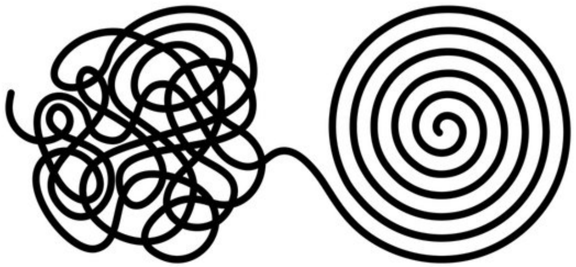
Low Frequency Analysis

Optical sensing offers a reliable foundation for methodologies requiring good quality low frequency data

Wavelet Analysis

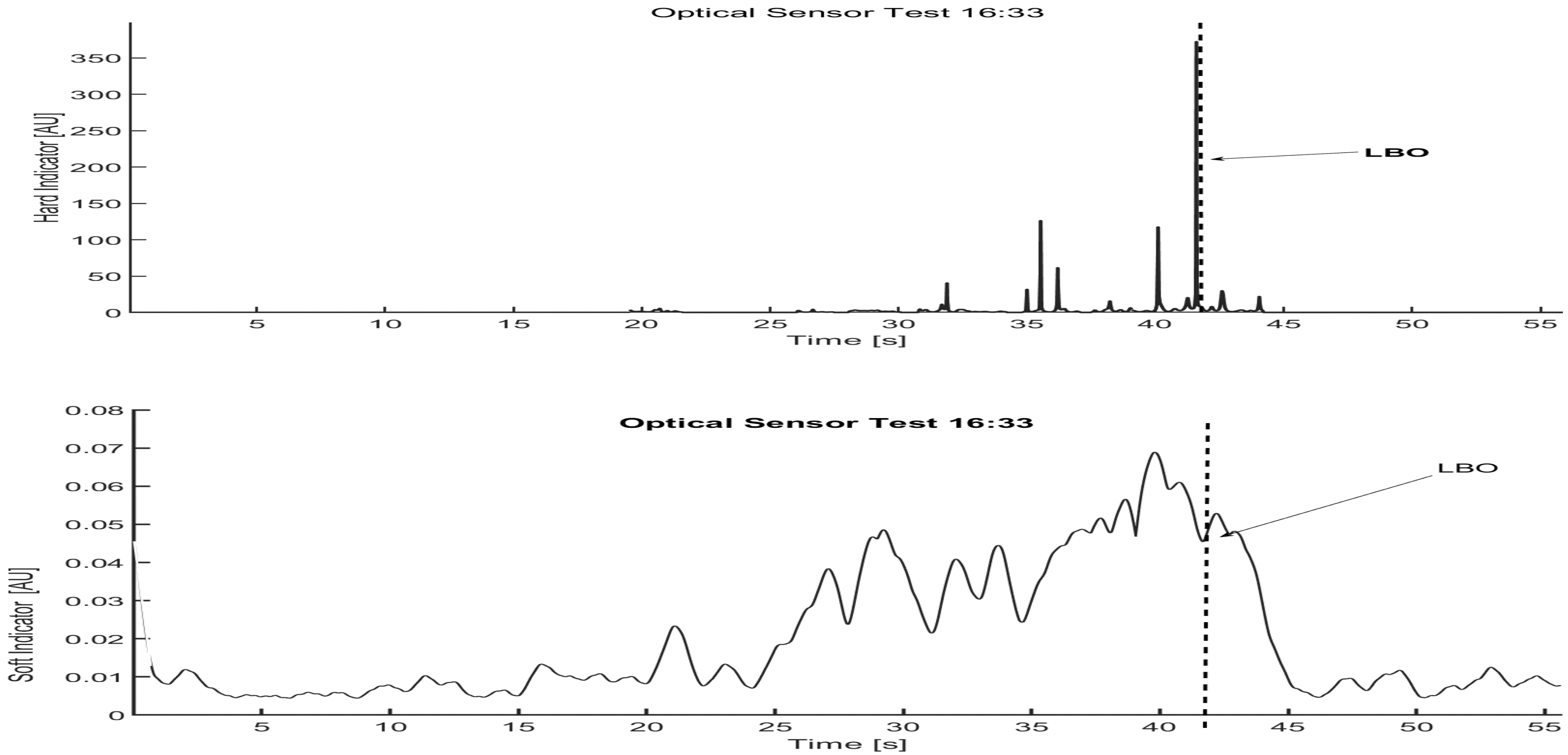


Fractal Analysis



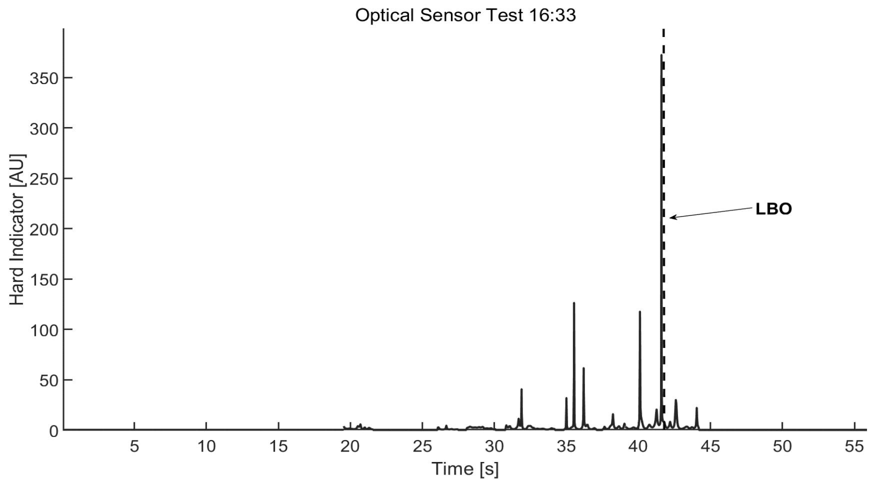
LBO precursor detection

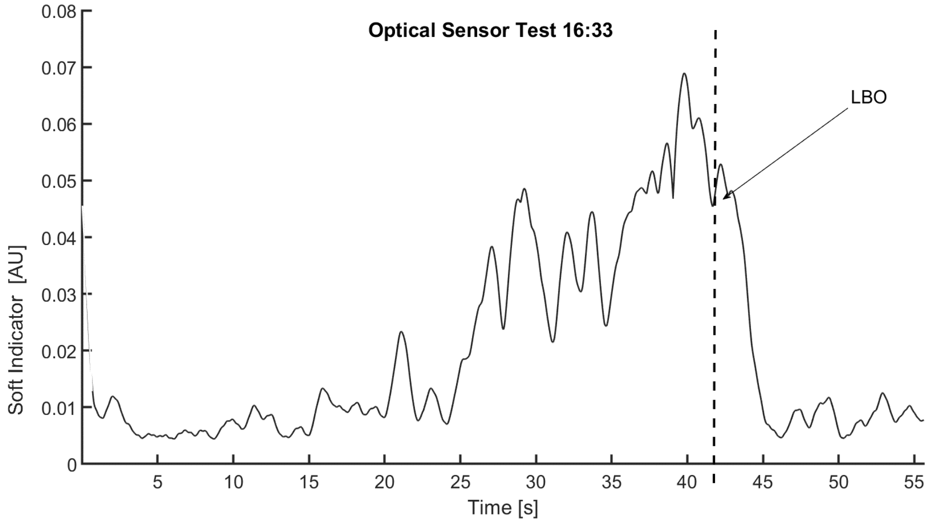
Wavelet Indicators

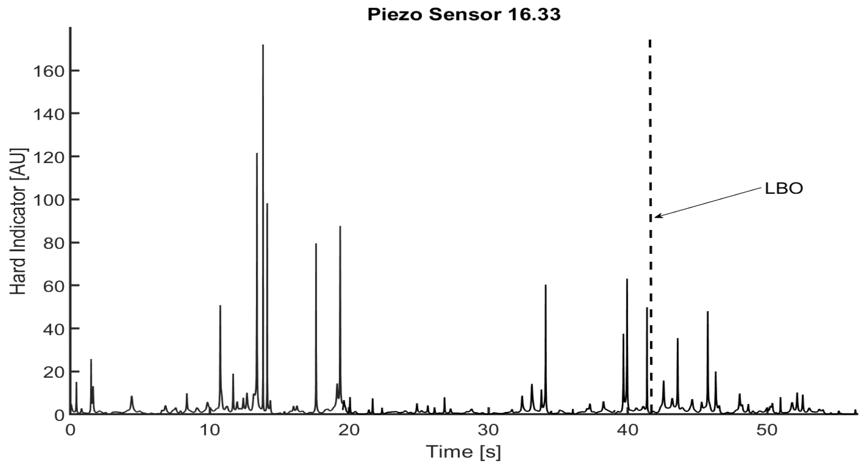


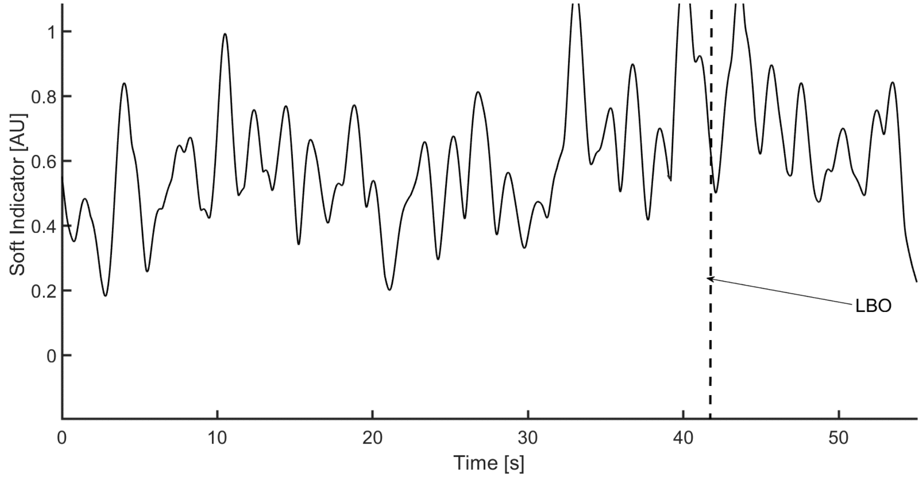
LBO precursors

Comparison optical vs piezo









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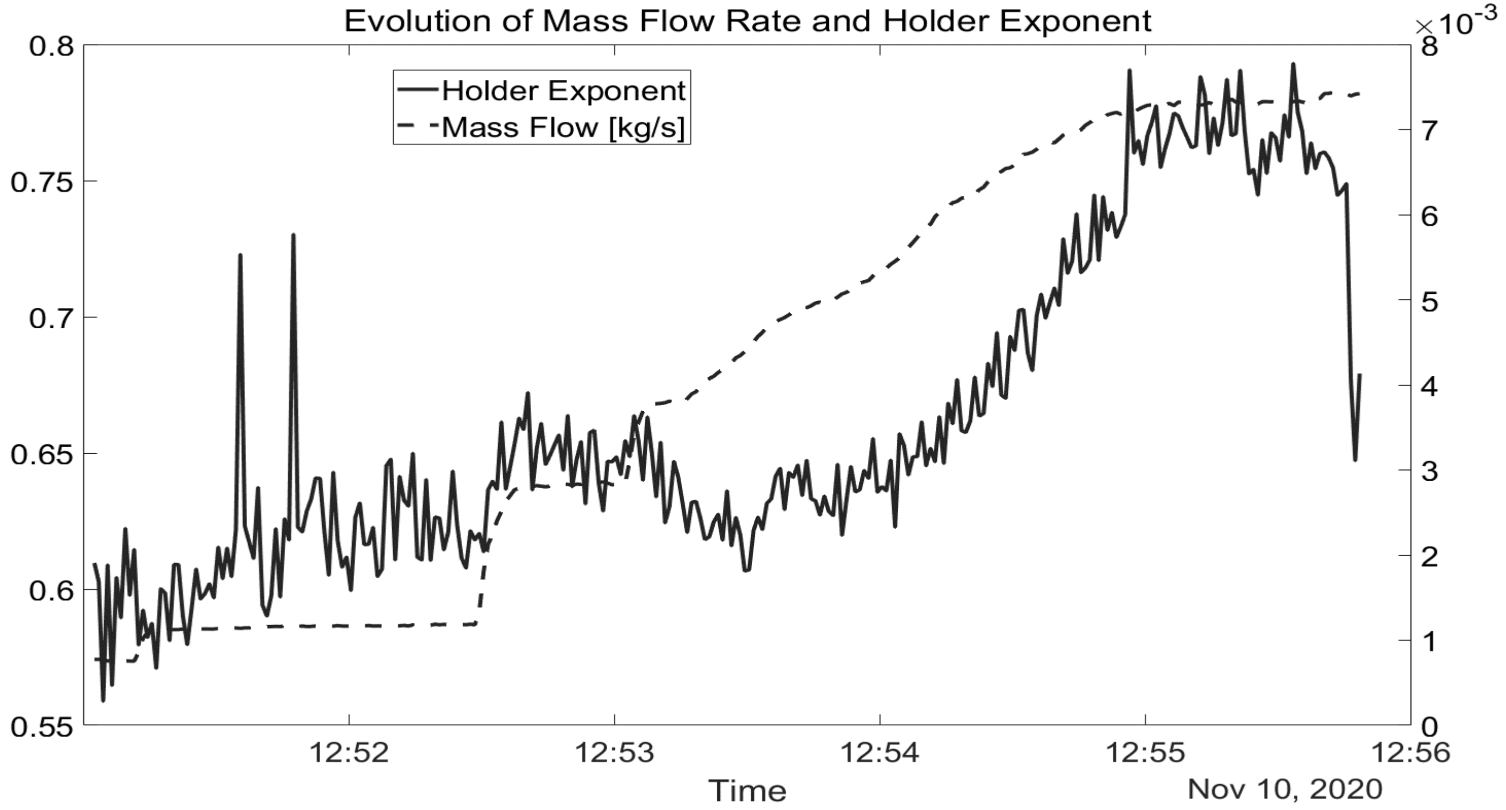
Fractal Analysis

Vs equivalence ratio

Decreasing the equivalence ratio by increasing air flow rate approaches the flame to extinction



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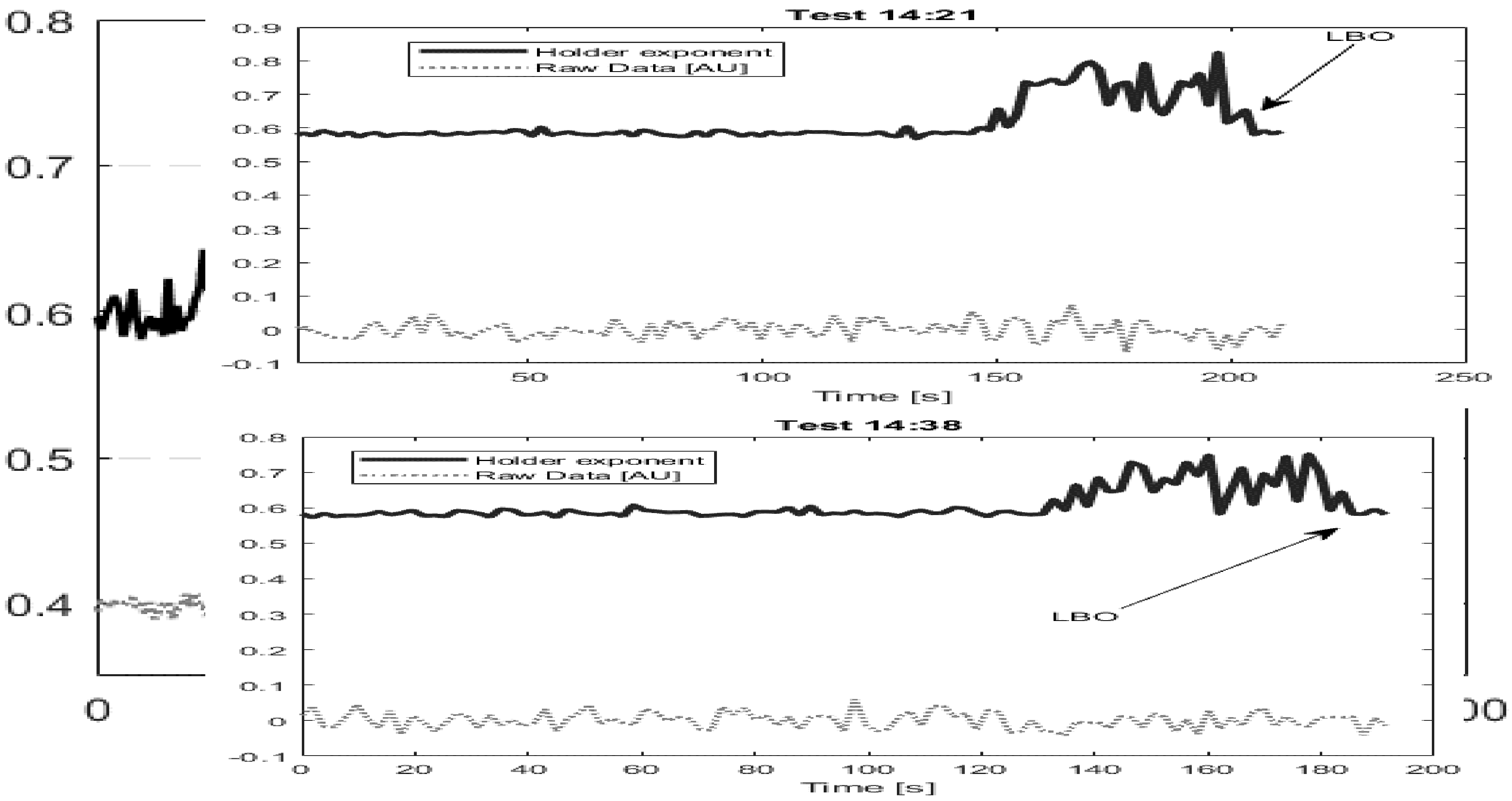
Fractal analysis

Evolution towards LBO

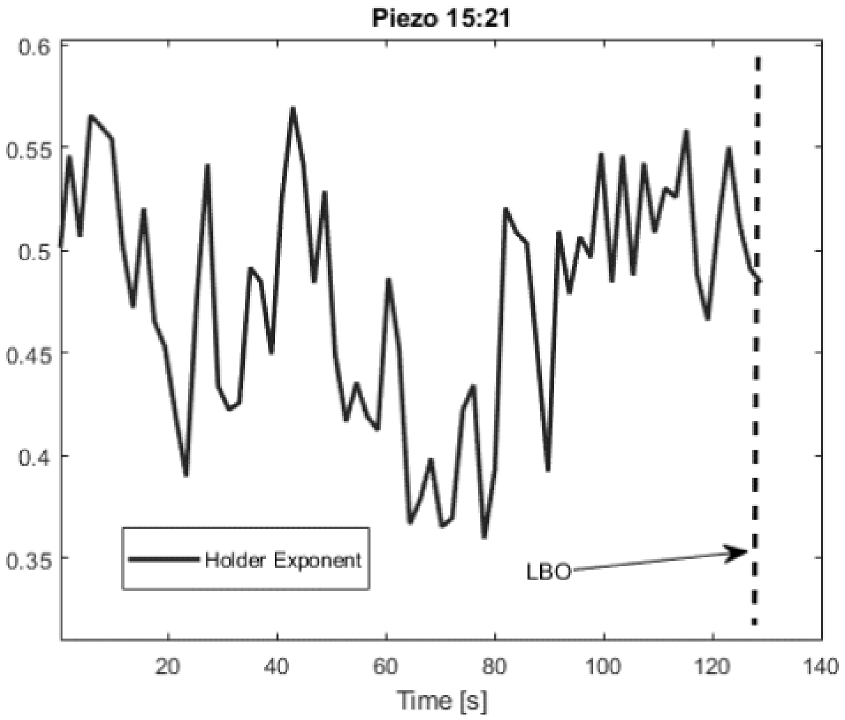


Fractal Analysis

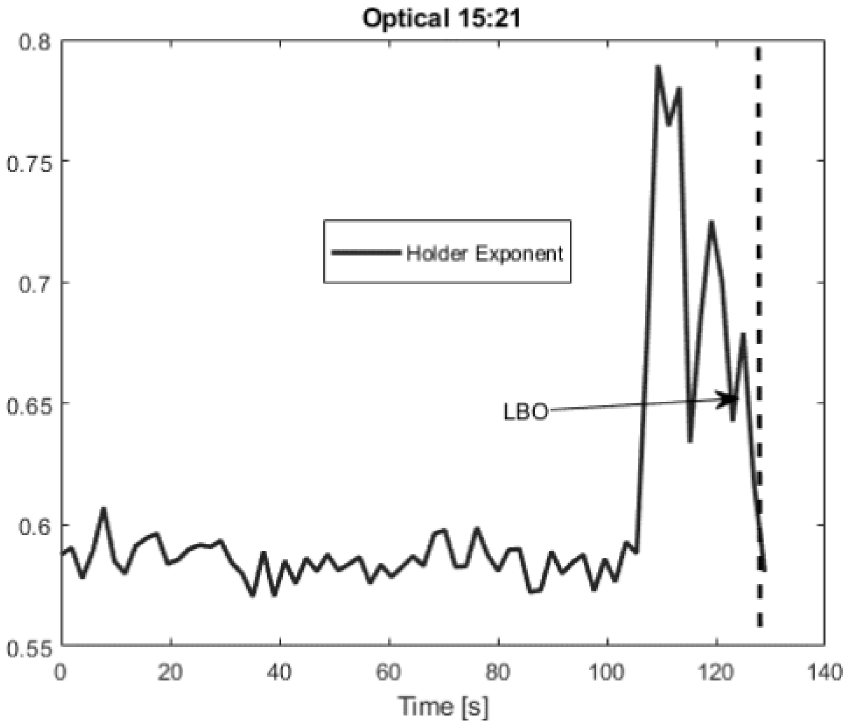
PE vs optical

The Holder exponent, derived from optical sensor measurements at low frequency, approaching the LBO event; pressure values in arbitrary units are plotted below (dotted line)

Piezo-electric



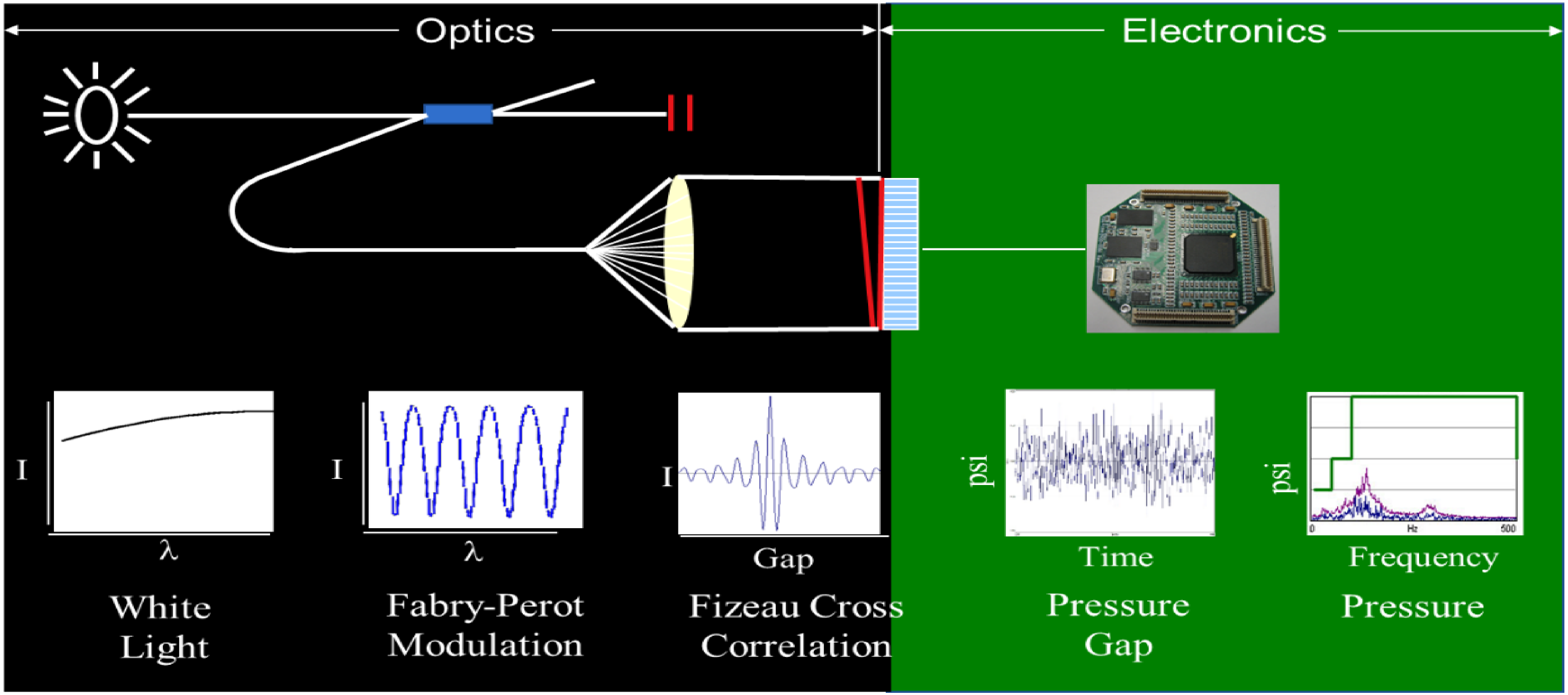
Optical



CONCLUSIONS

Recap

Sensing System



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Take away concepts

- The need to reduce emissions leads to the adoption of new strategies for energy production.
- Decarbonisation of gas turbines present challenges for combustion control that current sensors only partially meet.
- Optical sensors have characteristics that appear to be better suited to applications (temperature, EMI, SNR)
- Meggitt aims at becoming a world-class integrator of optical sensing technologies for Aerospace and Power Generation
- Meggitt system solution for dynamic pressure measurement is based on a combination of two interferometers and signal processing algorithms
- Meggitt optical interferometric pressure sensing system has been validated in operational environment
- Tests on novel Meggitt optical sensors had been conducted in an "ad hoc" campaign
- Pressure sensing method based on novel optical sensors matches the performances of the more mature piezoelectric sensing in most case however..
- The higher SNR of optical sensors at low frequencies provides a reliable foundation to monitor phenomena (LBO, Flashback) critical to transform gas turbines into low or zero-carbon emitting systems

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Current Developments

- HT Dynamic pressure sensor prototypes (550°C) for Energy applications
  - Tests on turbines since H1 2020.
  - Industrialisation phase to be completed by end 2021
  - Entry to market in 2022.

- New aerospace development of a HT (550°C) static pressure and temperature sensor and interrogator
  - Second Engine Test H1 2022

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References

Proceedings of Turbomachinery Technical Conference & Exposition
Presented by the ASME International Gas Turbine Institute
ASME Turbo Expo 2021
June 7-11, 2021, Virtual Conference, and Exhibition

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CHARACTERISATION AND VALIDATION OF AN OPTICAL PRESSURE SENSOR FOR COMBUSTION MONITORING AT LOW FREQUENCY

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ABSTRACT

This paper introduces a novel approach to monitor pressure dynamics in turbomachinery. This innovation is motivated by the need expressed by machine OEMs and end-users to detect and avoid combustion instabilities, as well as lean-blowout (LBO), in low emission combustion systems. Such situations are often characterised by a marked increase of pressure signals in low frequency range. The piezoelectric technology, conventionally used for pressure measurements, presents sensitivity and stability issues at high temperatures and low frequencies. Here a new paradigm for pressure sensing, based on optical interferometry, is characterised and validated.

The interferometric sensing system is designed to provide a larger range of measurement frequencies with better performance, in the low frequency range (<50Hz), while exposed to high temperatures. This unique feature allows the real-time observation of events, such as the specific behaviour of a low frequency flame dynamic, which is characteristic of an imminent LBO. This improved monitoring system will support an optimisation of the machine performance, leading to a safer, cleaner, more flexible and more cost-efficient operation for the end-user.

The novel measurement system has been characterised under non-reactive and reactive conditions within the frame of a joint study between Meggitt SA, Combustion Bay One e.U. and FH Joanneum GmbH. The technology is first described, including the relevant hardware and software components of the measurement chain. The different experimental set-ups and conditions are also illustrated. The results of the test campaign and their subsequent analysis are then presented, supporting the expected advantages over piezoelectric technology. In conclusion, a possible strategy for the detection of LBO precursors based on low frequency data is proposed.

NOMENCLATURE

CCD		Charge-coupled Device
c	[m/s]	Algebraic sum of the sound speed plus the mean flow speed of the air in a pipe-like resonator
DLE		Dry low emission
EMI		Electromagnetic interferences
f	[Hz]	Frequency
LBO		Lean blow-out limit
l	[m]	Pipe-like resonator length
OEM		Original equipment manufacturer
TTL		Transistor-transitor logic
λ	[m]	Wavelength
ϕ	[-]	Equivalence ratio

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1

Lean Blowout Sensing and Processing via Optical Interferometry and Wavelet Analysis of Dynamic Pressure Data

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ABSTRACT

Dynamic pressure transducers, based on the piezoelectric effect, represent the most widely adopted sensing method used for gas turbine combustion monitoring. However, piezoelectric technology shows some drawbacks when low frequency measurements are requested at temperatures exceeding 450°C. Because of more stringent environmental requirements, development efforts are nowadays focused on reducing NOx emissions. These resulted in advanced combustor designs that have been found to be particularly prone to trigger combustion instabilities and susceptible to blowout.

Observations and numerical simulations show that, close to flame extinction, pressure oscillations are characterized by high amplitude, low frequency fluctuations caused by a sequence of flame blowout and re-ignition events. Hence monitoring such phenomena requires good quality, low frequency data. It appears from early tests that optical sensing is positively addressing this aspect.

The pressure sensors based on optical interferometry, briefly described in this paper, are expected to provide by design more accurate measurements at low frequency and high temperature with respect to traditional piezoelectric sensors. By acting on combustion parameters, the test rig, described in the first part of the paper, has allowed to generate imminent blowout conditions in a controlled manner.

The data collected using the optical sensors in the vicinity of the flame extinction were analyzed with two wavelet-based signal processing methods designed to represent flame health indicators. The first algorithm simply exploits the well-known wavelets time/frequency analysis capability to carry out an investigation of signal variations at a lower frequency range up to 40 Hz. The second uses wavelets to extract non-linear characteristics of the signal related to the fractal dimension of the signal itself. The two algorithmic strategies have been applied to signals acquired with both piezoelectric and optical measurement chains.

The flame health indicators computed on data acquired by the optical sensor, reacted to changes in combustion dynamics preceding the blow out event. This was not the case with the data set acquired from the piezoelectric technology. The combination of optical sensing and wavelet analysis allows to define quantities that can be associated to the health of the flame and give hints about the imminence of the flame extinction.

1. INTRODUCTION

Increasingly restrictive emission standards compel power generation systems to operate within lean combustion limits in order to reduce the formation of NOx. Under lean conditions, the combustion process becomes more vulnerable to small dynamic pressure perturbations caused by load changes, variations in air temperature or humidity. When the air-fuel ratio shifts towards a lean mixture the flame speed gradually decreases from its value at stoichiometric conditions. Once the flow velocity of the fuel mixture exceeds the local flame speed of the reacting components, the flame becomes unstable and can be swept away by the flow from the unburned reactants and blowout can take place. A blowout event, i.e., the disappearance of the flame, caused by an excessive leanness of the reacting mixture is generally referred to as a lean blowout (LBO) and may occur due to a flame blow-off or flame extinction. LBO represents the main

FEEDBACK, COMMENTS & QUESTIONS ?

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THANK YOU

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