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

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

High-precision combustion monitoring is needed on power and propulsion gas turbine to survey the optimal steady state operation of the machine, possibly operating under low-NOx conditions [1, 2]. Furthermore it can identify transient behaviour and check that the recorded events are conform with a standard operation, or whether they reveal a need for maintenance (adaptive maintenance) at ignition, start-up, activation of the different combustion stages if needed, and changes in load [3]. The management of the operation within the safety margin near to the LBO for lean combustion systems, the proper distribution of fuel placement and the detection of diffusion flame modes, possibly generating particle matter, are all critical considerations in that respect. Most important is the detection of combustion instabilities, a situation that lean combustion systems are particularly prone to trigger and entertain [4, 5]. Finally, there is a need to provide quality data, indicators and precursors in near-real-time, to feed in predictive models and optimise the machine operations.

Because of the aggressive environment of the gas turbine hot core (high pressure, high temperature, elevated heat transfer, erosive flow and vibration), the instrumentation must be robust (resistant vs. mechanical strains, thermal strain, ageing and material fatigue, manipulation) and, at the same time, offer high fidelity and low-drift, be flexible (many parameters over a wide bandwidth of operation to survey with a single instrument), discrete (size, congestion, accessibility, fail-safe aspects) and universal (the principle is non-machine specific).

The standard technology used for gas turbine combustion monitoring is fast pressure transducer based on the piezoelectric effect [6, 7]. While meeting most of the requirements cited above, this technology is known to be temperature dependent, with some drawback on its capacity to perform measurements at low frequency [8].

An optical pressure sensor is used in this study. The upside of a fast pressure transducer based on optical interferometry is threefold. First, it allows a larger range of measurement frequencies with better stability, especially in the lower frequency range, i.e., less than 50 Hz. This low frequency band allows the quasi-real-time observation of precursors, such as the specific noise of a low frequency flame dynamic, which is a characteristic of an imminent LBO. This feature is unique to the optical principle, which exposes only the passive part of the sensor (the membrane) to harsh environmental conditions, while the active elements are remotely located under ambient conditions. Second, the measurement is independent from temperature and static pressure at the measurement point. Finally, the measurement is also intrinsically insensitive to vibrations or EMI.

All of these assertions are verified in this work. Particular attention is paid to the behaviour at low frequencies, where, in the presence of high temperature, the performance of the piezoelectric sensors reaches its limits. The methodology is to systematically compare the optical interferometry system with its piezoelectric counterpart. The paper firstly introduces the optical system principle. The test setup and procedures are also described. The results are then analysed. At the end of the article, some preliminary results are presented on the detection of an imminent LBO, underlining the importance of high fidelity measurements provided by optical fast-pressure sensing in the low frequency range.

AN ACOUSTIC SENSING METHOD BASED ON INTERFEROMETRY

In gas turbine monitoring, all sensors are based on electrical working principle technologies such as piezoelectric, piezoresistive and capacitive measurement principles. For every individual sensor, an electrical readout signal is sent through an electrical wire connected to the engine electronic units. Various piezoelectric materials have extensively been researched for high-temperature (HT) applications [9] and each one of them has its own unique advantages and drawbacks. In general, piezoelectric sensors show performance limitation under elevated temperatures in the low frequency range. The reason is twofold. First, the load and leakage resistance, which has to be large to sense low frequency signal, decrease with the temperature of about a factor 10 every 100°C [10], hence reducing the sensitivity to the signal. Then, at the same time, high temperature favours phenomena like twinning and pyroelectricity, which increase the measurement noise.
Fibre optic sensing technologies [11–15] provide several advantages over piezoelectric sensing technologies, such as:

(i) Insensitivity to pyro-electric effects [8];
(ii) Inherent insensitivity to external perturbations, i.e., electromagnetic interferences and radio frequency interferences, vibrations;
(iii) Long to very-long range measurement with negligible signal decay;
(iv) Distributed sensing, i.e., the possibility of multiplexing a large number of individually addressed sensing points.

Therefore, the replacement of piezoelectric sensors with fibre optic sensors will particularly be desirable for many combustion monitoring applications, especially the ones requiring monitoring of low frequencies [16, 17].

This new measurement system can be subdivided into an optoelectronic interrogator, an optional optical extension cable and an optical transducer. The subsystems are connected together so that light signals are exchanged between them through optical fibres, as shown in Fig.1.

The interrogator sends a light signal out to the optical transducer through the optical extension cable. The transducer is composed of a sensing element made of a Fabry-Pérot interferometric cavity. The cavity is composed of two semi-reflecting glass mirrors. One mirror is directly connected to the optical fibre and the other is bonded to a membrane, such that the cavity length (hereafter referred as gap) varies when the membrane is subjected to pressure. Therefore, when pressure is applied, the membrane is deformed and the gap is proportionally reduced.

The light in the Fabry-Pérot cavity is frequency-modulated as a function of the acoustic pressure exerted on the sensing element (membrane). Within the interrogator, the frequency modulation of the light is converted into spatial modulation via a Fizeau interferometer. The spatially modulated light is recorded by a CCD. The signal is then processed with ad hoc signal processing methods to extract the dynamic pressure information: this signal is related to the displacement in real-time of the fringes of the Fabry-Pérot interference pattern.

Fig.2 shows the optical probe used in this study. The diaphragm at the tip of the probe has a dimension of a few millimetres. The whole body of the probe is a flexible shield surrounding the optical fibre of reduced dimensions, able to slide in and take position in locations that are not line-of-sight with the measurement tap.

The mechanical as well as the thermal strains were risen progressively, always comparing the response of both types of sensors exposed to a similar excitation, and verifying the absence of drift. The maximum pulsation rates to which the sensors were exposed were in the magnitude of 10 mbar peak amplitude (cold tests with the probes in total pressure mode facing the siren pulse jet achieving 150+ dB SPL, see [18]). The probes were exposed to temperatures up to 400°C over two hours duration, the combustion rig being operated up to 20 kW. It is important to mention that not only did the probes survive the tests, they also showed a similar response to calibrated pulse flow, both at the beginning and at the end of the test sessions.

**FIGURE 2:** The optical probe with the fibre connector (top left) and the probe head (bottom right)

**FIGURE 3:** Cold flow test configurations using the Siren 3G
EXPERIMENTAL METHODS

The test sessions analyse the optical probe’s response to several realistic scenarios representative of gas turbine combustion, and therefore reproduce these conditions in a controlled, precise and repeatable manner. Of particular interest are the optical sensors’ response when exposed to realistic levels of acoustic pressure fluctuations (several millibars, peak amplitude), their response when exposed to perturbations such as vibration or electromagnetic interference, their capacity to describe the machine operation including monitoring of the ignition, the power changes, and the flame regime - before all whether it is premixed of diffusive, and their capacity to identify a flash-back, to detect combustion instabilities and to identify a coming LBO (precursor).

Test setup

An equipment, similar to the one used by Giuliani et al. [6], was also used in the frame of this study, meaning the same piezoelectric fast pressure transducers and accelerometers were used for comparison and vibration assessment issues. For the acquisition, Meggitt XMV card for condition monitoring was used to perform order-tracked (or phase-locked) measurements. It was completed by Meggitt XMC acquisition card for combustion monitoring that has similar specifications to the XMV card (16 channels of acquisition, real parallel with up to 100 kHz of acquisition frequency per channel), allowing peak-location per defined frequency band. Meggitt VibroSight software suite was used for the live monitoring, and for a part of the post-process.

This equipment was set up for the sole purpose of the study. It is representative only and not restrictive, when it comes to the use of the optical probes.

Cold flow experiments

The cold flow experiments are briefly discussed only because they are instrumental to the combustion tests. They were mainly used to get familiar with the set-up of the optical sensors, which requires different cares that the ones for two-wire transducers. For instance, the cleanness of the interfaces of the fibres is of extreme importance regarding the signal quality, so that it must be checked and cleaned if necessary when laying the cables and doing the optical connections. This also allowed us to test our instrumentation, decide which ranges of frequencies are worth studying (0-2 kHz with a focus on the 0-600 Hz region), and set our acquisition configurations.

Fig.3 shows the different configurations tested using a siren as a flow exciter (the siren used is a model 3G from Combustion Bay One e.U., Graz, Austria [18]). This device also provides the synchronisation (or square wave pulsation under the shape of a TTL signal) with the phase-locked measurements. The first configuration a) allows to generate strong pulsations, interpreted at
the level of the sensors as fluctuation of dynamic pressure in the pulse jet. The second and the third make use of a pipe of length \( l \) as a resonator, excited by the siren and amplified until limit cycle occurs. In configuration b), the conditions are slightly sub-atmospheric and in configuration c), using a 1kW extractor, the probes are in depression at -200 mbar rel. For all configurations, the pipe of length \( l \) will act as a half-wave resonator if the nozzle of the siren is not choked (the fundamental wavelength is \( \lambda = 2l \), the fundamental resonant frequency is \( f = c/(2l) \) and all subharmonics), and as a quarter-wave resonator if the nozzle is choked (\( \lambda = 4l \), \( f = c/(4l) \) and all odd subharmonics).

This was the first time that configuration c) was tested. Using quite a simple equipment, peak amplitudes up to 8 mbar could be achieved.

Accelerometers were also mounted at the probe locations, investigating two directions, perpendicular to the flow and in direction of the flow, which happened to show similar results and therefore an isotropic vibrational behaviour. This is something similar to what we observed later on on the combustion test rig.

In all cases, there was a good match between the recordings at similar locations.

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**Hot flow experiments**

The atmospheric combustor, shown in Fig.4 (top), is based on the MethaNull set-up, described by Giuliani et al. [19]. A schematic representation of the set-up and how it is combined with the siren is shown in Fig.5. A two-stage burner, where pilot and main burners are coaxial, is generating a swirl-stabilised, premixed flame of air and propane (propane C3H8, type UN 1965 mixture C, 46.3 MJ/kg, 2 kg/m3 at standard conditions). The flame evolves in a SQ1 glass liner of 100-mm diameter and 400-mm length.

The different probes locations are displayed in Fig.4 (bottom). They were flush-mounted on the combustor with inner diameter 200 mm. The two optical probes were mounted near to each other. All probes were placed at the same distance from the front plate, i.e., 75 mm, except for the accelerometer mounted 150 mm away from the front plate. They were also situated in the cooling flow evolving around the flame tube. The cooling slots were modified from 100% opening for the flash-back tests to 10% opening for the endurance tests, letting the sensors warm up on the one side, but also reducing the cooling noise on the other.

In order to observe the transition premixed-diffusion flame, a Rayleigh-Criterion-Probe with 4 photodiodes in the visible, red, green and blue spectral domain (also called emotion probe [20]) is assembled with the piezoelectric sensor CP#2. The S3R ignition system, using a premixed ignition flame, is described by Andracher et al. [20] and Moosbrugger et al. [21]. It is also used to generate EMI (without gas) as well as the ignition detection tests.

Tests were driven up to 20 kW thermal power. Both burning air (pilot + main air) and cooling air mass flow rates could be set up to 8 g/s. The set-up and laboratory structure are shown in Fig.4 (top). Since this burner is a laboratory burner, LBOs were observed in the \( \phi = 0.6 \) region at low power, degrading down to the \( \phi = 0.7 \) region under elevated power. It can be explained by the stronger jet dynamics at elevated power, which push the flame away from the front plate in the secondary zone, making it more fragile.

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**RESULTS AND DISCUSSION**

Pressure fluctuations in the range of 2 mbar peak amplitude were measured on flush-mounted locations in the pressure casing during the combustion tests. This is up to four times lower than the values obtained in the cold tests with organ-type pipe resonators. Despite the fact that the optical probes are operating bottom of scale, they qualified to detect and analyse all of the following events.

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**FIGURE 6**: EMI from the ignition and time signals from the optical probe (top), piezoelectric fast pressure transducer (middle) and accelerometer (bottom)
Ignition and EMI

At ignition, the optical probes are much less disturbed by EMI than the piezoelectric transducers and accelerometers, as shown in Fig.6. The operation of the spark igniter was conducted with and without gas, always showing a very strong perturbation on the piezoelectric sensors, while hardly perceptible on the optical probes, which can therefore offer a better description of the ignition process.

This might be of high relevance for power gas turbine with frequent start and stop, from an operational, cost as well as environmental standpoint. The success rate of the ignition process is an indicator of adaptive maintenance, making its high precision measurement critical. Furthermore, a high-fidelity combustion monitoring at ignition allows a short-response abort sequence when the ignition fails, that in turns shortens the duration for flushing the fuel circuits before the next try.

Premixed and diffusion flame modes

Fig.7 shows in the upper plot the light chemiluminescence in the red component, extracted from the emission probe. When the level is high, the flame is diffusive and laminar, producing a lot of particle matter. When the chemiluminescence is low, meaning up to 1000 times less intense, the flame is premixed and turbulent. To achieve these figures, the flame power was set at 5 kW, and the burning air was varied from 0.5 to 3 g/s.

A band analysis in the frequency domain [50-300 Hz] identifies this transition with both optical probe (red curves middle and bottom) and piezoelectric pressure transducer (blue curve middle and bottom). Both measurement principles qualify for the detection of diffusion flame, and can establish, via a correlation, the amount of particle matter (soot), which is produced in real-time. Based on such information, it is possible to trigger an alarm and/or to regulate the combustion back into a more desirable blue flame mode.

Flashback detection

A flashback is initiated on purpose by acting on the cut main air / cooling air to the advantage of the latter. When the main gas injection achieves more than 4 kW a flashback occurs, with the flame travelling back into the plenum. This sequence is represented six times in a row in Fig.8, with the waveform of the piezosensor at the top, and the low frequency band analysis of both optical probes in the middle and at the bottom.

Both the piezoelectric fast pressure transducer and the optical probe detect flashbacks. An effective way to study flashbacks is to study the waveform of the acoustic pressure directly. Another way is to study the bands in the frequency domain. In the low frequency band of the optical probes [1.5-5 Hz], the double-peak structure at each cycle coincides with the flashback events at a given frequency. The good correlation between the two optical probes is highlighted by the frequency peaks observed in the lower frequency band. The patterns are synchronous and the shapes are very similar.


FIGURE 8: Flashback detection. Top: recording of the noise of a series of flashbacks repeated 6 times by a piezosensor. Middle and bottom: low-frequency band analysis for both optical sensors in the [1.5-5 Hz] range.
Combustion instability

The procedure shown in Fig.9 is called the "Koelner Dom" test [18]. It consists in a first frequency ramp excitation at maximum amplitude, during which thermacoustic eigenfrequencies of the flame are identified. After that, these frequencies are interrogated separately at constant and at variable amplitude.

The optical sensor and piezoelectric sensors show a good agreement in amplitude response (top plot) as well as a well-repeated phase at constant frequency (lower plot). Therefore, the optical probe measurement coincide with the piezoelectric transducer measurements in terms of amplitude as well as in terms of phase delay. Both types of sensors qualify for combustion instability detection. They also qualify for active control purpose [22], based on the phase information they deliver. In the case of a low frequency thermoacoustic instability of humming or rumbling type, the optical probe is likely to describe the physics of the fundamental mode more precisely than the piezosensor.

Imminent LBO

A controlled LBO is initiated at 16 kW by gradually increasing the mass flow of burning air, until a strong flame dynamic moving up and down along the liner is observed, while a characteristic coughing noise is heard. The lean flame fights for stabilisation and loses its footing while the combustor walls cool down, moving the heat strain downstream in the flame tube. The air mass flow rate is maintained over periods of half a minute or so, during which these brutal motions are clearly observable by all sensors in the time domain, as displayed in Fig.10 (top), where the LBO happens at 15:23:48 (see the signal patterns situated near the arrows at about nine tenth of the plot’s length). When the blow out happens, the RMS of the signals falls down.

The spectrogramme, displayed on Fig.10 (bottom), shows that the frequency signature below 100 Hz (104 Hz precisely) could be used to define a precursor using the fast pressure optical signal. Low frequency contents are highlighted when the flame enters its imminent LBO dynamic. It remains steady state at constant lean mixture feed. The abrupt fall of this peak detection in the band [50-300 Hz] marks the LBO event.

Due to the aperiodic nature of the flame’s instability near the LBO, and more generally to deepen the study of the non-stationary frequency behaviour, time/frequency analysis has been applied to investigate the signal more accurately by means of a wavelet approach.

The Morlet wavelet transform introduced in the next section has been used to produce scalograms from the fast pressure signals. Fig.11 illustrates the continuous wavelet scalogram for both optical (top) and piezoelectric (bottom) sensors, close to the LBO region observed in Fig.10. A sharper transition in optical signal at time t=9s is visible, corresponding to the LBO event, hence highlighting the higher precision of the optical probe at low frequency.

LBO PRECURSORS

Lean blowout is a major technical challenge for dry-low emission (DLE) combustion systems. Currently, blowout is mostly avoided with a wide margin above the uncertain LBO limit. The ability to sense precursors can, therefore, provide significant payoffs.

The potential of optical sensor to produce less noisy signals at low frequencies opens the way for a more effective time frequency analysis of transient phenomena. These include the detection of an impending LBO.

Based on the ideas presented by Kabiraj et al. [23] and by Nair and Lieuwen [24], three different indicators of an impending blow out were developed and verified during the test campaign. The algorithm used is detailed by Nicchiotti and Soliniski [25].
The first two indicators are based on the analysis of low frequency transients. The signal is initially subjected to a wavelet decomposition of the signal $X$ so that:

$$W_x(j,k) = \int X(t)2^{-j/2}\psi_0(2^{-j}(t-k))dt$$

where $W_x$ is the wavelet coefficient, $\psi_0$ is the "mother" wavelet with a compact time support, $t$ is the time, $j$ is the dyadic scale parameter, and $k$ relates to the shift parameter.

Morlet and Morse wavelet basis have been experimented and Morse basis has been found to provide better results. Morse wavelets are particularly useful for analysing localised discontinuities and events. Because they are parametrised by two values ($\beta$ and $\gamma$), they are more versatile than the Morlet wavelet which has only one parameter.

**FIGURE 10**: LBO sequence at 16 kW, with the LBO event happening at 15:23:48 (arrows). Top plots: analysis in the time domain (two optical probe followed by two piezoelectric transducer waveforms). Bottom plot: frequency analysis of the optical probe #1, first with a band analysis in the low frequency range [1.5-5 Hz], and spectrogram of the same sensor (bottom) showing the near LBO signature in the low-frequency domain.

**FIGURE 11**: Comparison of scalograms [a.u.] resulting from a wavelet transform applied on both optical (top) and piezoelectric (bottom) signals, close to the LBO region observed in Fig.10. The LBO event happens at 8.5s (arrows).
Morse wavelets are defined in the frequency domain as:

$$\Psi_{\beta,\gamma}(\omega) = \int \psi_{\beta,\gamma}(t) e^{-i\omega t} dt$$

(2)

where $\gamma > 0$ is the shape parameter and $\beta > 0$ is the oscillation control parameter. In our tests we set the values $\gamma = 8$ and $\beta = 1$, which allowed the optimal adjustment for refining localisation in frequency and time.

The former indicator compares the relative intensity of the wavelet coefficients $W_x$ in a frequency range between 3 and 30 Hz and we named it hard indicator $I_H$ so that:

$$I_H = \frac{\max(W_x) - \min(W_x)}{\text{mean}(|W_x|)}$$

(3)

where max, min and mean indicate respectively the maximum, minimum and average operations.

The latter follows the evolution of the statistical dispersion of the coefficients $W_x$ in the same range of frequencies and we named it soft indicator $I_S$ so that:

$$I_S = \frac{\text{std}(W_x)}{\text{mean}(|W_x|)}$$

(4)

where std is the standard deviation operation.

As shown in Fig.12 on an LBO sequence happening on a flame at 5.5 kW and called test "16:33" in the text, the hard indicator demonstrates in most cases good LBO detection capabilities, but does not appear suit able for a continuous measurement of the state of the flame as it presents sharp and sudden transitions which do not really allow to anticipate the extinction of the flame.

Fig.13 illustrates the behaviour of the soft indicator during the same experiment. The soft indicator shows a more gradual evolution as the flame approaches extinction, increasing as the LBO approaches. The soft indicator therefore seems to be able to better represent the state of health of the flame itself. Even if the soft indicator behaves like a LBO precursor in many cases (Fig.14), when computed on "optical" data, it has been observed that it is mainly relevant when the blow-out is preceded by a flame cough phase, where the main flame detaches and reattaches to the flame holder. Indicators are less reactive to LBOs which occur in a more smooth, continuous and silent way.

The two indicators were computed also using measurements collected with piezoelectric sensors. Results on piezosensors are presented in Fig.15. A comparison with the results presented in Figs. 12 and 14 clearly show how indicators computed on optical sensors provide a better assessment of the flame status. As mentioned, hard and soft indicators do not prove yet to be adequate for all the possible modes where flame extinction can occur. This approach is however promising.

A second theoretical way has been approached to create LBO precursors. It is based on the fractal dimension analysis of the signal already proposed by Kabiraj et al. [23].

Under lean conditions combustion process is vulnerable to small perturbations. Such low frequency perturbations affect local regularity and the scaling behaviour of the signal. In addition to wavelet time-frequency investigation, we tried to identify LBO precursors by analysing the fluctuation of the local regularity across time when LBO is approaching as suggested by several authors [23, 26, 27]. This task has been accomplished by using multifractal analysis.
The concept of multifractality was originally introduced by Mandelbrot [28] in the context of turbulence. The purpose of multifractal analysis is to study functions or signals whose pointwise regularity changes in time. Wavelet leader multifractal analysis (WLMA), also known as wavelet transform modulus maxima (WTMM) [29, 30], is a method which allows to estimate scaling exponents and the corresponding multifractal features of the signal.

Wavelet leaders are a subset of wavelet transform coefficients $W_x$ representing the local maxima of the coefficients across different scales.

In our case wavelet leaders $L_X$ of the signal chunk $X$ are defined as the local maxima of the wavelet coefficients $W_x$ in 3 consecutive scale intervals i.e.:

$$L_X(j,k) = \max(W_x(j,k)) \quad \forall j \in [j-1, j+1]$$  \hspace{1cm} (5)

The Holder exponents of signal $X$ and its singularity spectrum can be determined from wavelet leaders [31]. The singularity spectrum is estimated using structure functions determined for the linearly-spaced moments. Holder exponent represents the power law for a different mono-fractal process. For instance a Holder exponent $\alpha$ computed at $t=t_0$ models a mono-fractal process $X(t)=|t-t_0|^{\alpha}$ at $t_0$.

Expecting a change in local regularity properties of the low frequency signal, as discussed in several publications [23,26,27], the described multifractal analysis has been performed on pressure signal recorded by optical sensor. We analysed the evolution of Holder exponents whilst varying the equivalence ratio in the combustor. As an early but promising result, Fig.16 shows the behaviour of the Holder exponent and the air mass flow rate as a function of time during one of our LBO tests (fuel rate is kept constant). Decreasing the equivalence ratio by increasing air flow rate brings the flame closer to extinction, which happened at about 12:55:45. The plot in Fig.16 shows that flame health worsening is well captured by the Holder exponent.

The test campaign revealed that the hard and soft indicators are more reliable than the Holder Exponent as LBO precursor when the flame shows a strong come and go dynamic through the liner, and blows out in a sudden and brutal manner. However, Holder Exponent has proven to be complementary to the hard and soft indicators, proving to better detect extinctions in
FIGURE 16: Holder exponent used as LBO precursor, making use of the optical probe signal

the case where the lean flame re-stabilises before it is completely extinguished ("soft vanishing").

CONCLUSION

The test campaign run during this investigation has demonstrated that an acoustic sensing method based on optical interferometry can match the performance of the more mature piezoelectric sensing method commonly used on combustion dynamics monitoring. In terms of acquisition and equipment technology, the optical probe intrinsically qualifies for a completely digital measurement chain.

Moreover, the low frequency data acquisition capability of optical sensors opens the door to a more reliable foundation to compute indicators of impending LBO. This distinctive property has made it possible to develop flame status indicators that can give warnings about an imminent LBO.

The first results on such indicators are promising and show that this technology has potential to become the future standard of combustion monitoring. The combination method and instrument is promising, and could lead to a new generation of monitoring tools probably outperforming the current state-of-the-art when applied to extremely aggressive environments, such as the hot core of a gas turbine.

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