Comparison of Different Instability Criteria for the Characterization of the Dynamical State of Combustion Systems

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Abstract

Although investigated for many years, real-time monitoring of combustion dynamics is still an important issue in modern gas turbine operation. In this article, attention is focused on two quantities, radiant energy, and pressure, that can be sampled in combustion systems. Based on such quantities, and with the aim of selecting the best operational index to detect instability precursors, different strategies are here defined and compared.

Introduction

Great effort is currently dedicated to the development of fuel-flexible lean-premixed gas turbines able to burn fuel mixtures with variable hydrogen content. Lean premixed combustion offers the advantage of low NO_x emission, but it is highly sensitive to external perturbations, especially to variations in the equivalence ratio of the mixture; this issue tends to promote the onset of self-sustained large amplitude pressure oscillations called thermoacoustic instabilities, due to the resonant coupling between unsteady combustion processes and pressure waves in the combustion chamber [1,2]. Such instabilities enhance heat transfer to combustor walls, deteriorate combustion efficiency, increase pollutant emission, and, in extreme cases, can produce structural damages leading to the loss of control of the power plant or propulsion system. While the global mechanism of thermoacoustic instabilities is known, identifying in real-time the responsible initial mechanism and its precursors remains a difficult task.

This article describes the results of real-time monitoring of a turbulent lean-premixed flame by means of an optical system called Optical Diagnostics of Combustion (ODC), developed, validated, and patented in ENEA [3-6], and a pressure transducer. With the aim of looking for the best index for real-time identification of instability precursors, different indexes are suggested and compared.

Monitoring quantities and sensors

Turbulence-chemistry interaction results in an unsteady variation of the flame shape and the local reaction rates, thus, causing a broadband noise level, commonly referred to as combustion noise. During combustion instabilities three physical mechanisms interact in a highly nonlinear and unsteady manner, i.e., vortex motion (vorticity), heat release (entropy waves) and acoustic fluctuations, and the flame itself can be influenced by noise and acoustic waves up to a resonant interaction.

The main and direct outputs that an observer in front of a combustion process can capture are radiant energy (light emission), thermal energy (light emission in the NIR or IR range) and noise (pressure waves).

The most basic measurable quantity to monitor and characterize unstable combustion is dynamic pressure [1], by means of microphones and pressure transducers. Since acoustic waves propagate throughout the entire combustion system, they can be placed far from high temperature regions. In enclosed systems, flames can be strongly influenced by the acoustic characteristics of the combustion chamber; therefore, the acoustic signature of a burner may change when it is installed in different combustion chambers (including the effects of dampers and cooling systems).

Many features make radiant energy sensors appealing. Such devices are optical; hence, they are not intrusive. Exhibiting large bandwidth up to several kHz or even tens MHz, they are suitable for the study of flame dynamics and combustion instabilities or unsteady pulsed combustors as well as for the development of fast-response controllers.

The naturally occurring flame chemiluminescence in UV-VIS range is related to heat release and has proven to be extremely useful in characterizing unstable combustion in lean premixed combustion. Chemiluminescence is the radiative emission from electronically excited species. Its intensity is determined by the competition between the chemical reactions that produce such excited species and the collisional quenching reactions. In particular, emission from OH (282.9 nm; 307-309 nm) and CH (387 nm; 431.5 nm) radicals, occurring at distinctly different and relatively narrow-wavelength intervals, are good indicators of heat release rate [7] and flame front location. Single detectors, such as photomultipliers (PM), photodiodes (PD) or avalanche photodiodes (APD), coupled with bandpass filters at selected central wavelengths, are the most common option to detect radiant energy [4].

Classical criteria for thermo-acoustic instabilities

The classical *Rayleigh's criterion* [8] states that when the pressure and heat-release fluctuations, p' and H_R', are in phase, a system becomes unstable:

$$\int_V \int_0^\tau p' H_R' \, dt \, dV > 0 \tag{1}$$

When the magnitude of the phase between p' and H_R' is less than 90° they are in phase, and the instability is locally amplified. Conversely, when these fluctuations are out of phase (i.e., in the range 90°-180°), the instability is damped.

Rayleigh's criterion is a necessary but not sufficient condition for instability to occur (loss mechanisms are neglected). *Chu's criterion* [8] is more accurate:

$$\int_V \int_0^\tau T' H_R' \, dt \, dV > 0 \tag{2}$$

It requires temperature and heat release fluctuations, T' and H_R', to be in phase for the instability to grow. An extended version of the above criteria also exists [8].

The suggested experimental instability criteria

Once introduced classical instability criteria, it is worth looking for some measurable integral (in space) quantities linked to T' and H_R', that can be correlated to pressure fluctuations p'. It is observed that total radiation emitted by flames consists of two types of sources: the first one is chemiluminescence, while the second one is thermal emission associated to the Planck function [4,9,10]:

1. since the intensity of light emission (radiant energy) in the UV-VIS range (chemiluminescence) is proportional to the production rate of some molecules (e.g., CH, OH, C2 radicals), chemiluminescence can be used as an indicator of reaction rates and heat release rate fluctuations, i.e., H_R' [7];
2. since the intensity of light emission in the IR range (thermal energy) is proportional to the temperature of the field according to the Planck function, it can be used as an indicator of temperature fluctuations, i.e., T' [9,10].

With these statements, it is possible to evaluate instantaneously and in real-time three instability criteria, T'-H_R' (mimicking the Chu's criterion), p'-H_R' (mimicking the Rayleigh's criterion), and p'-T', by cross-correlating the three quantities, H_R' and T' being measured via radiant energy sensors, and p' via acoustic sensors.

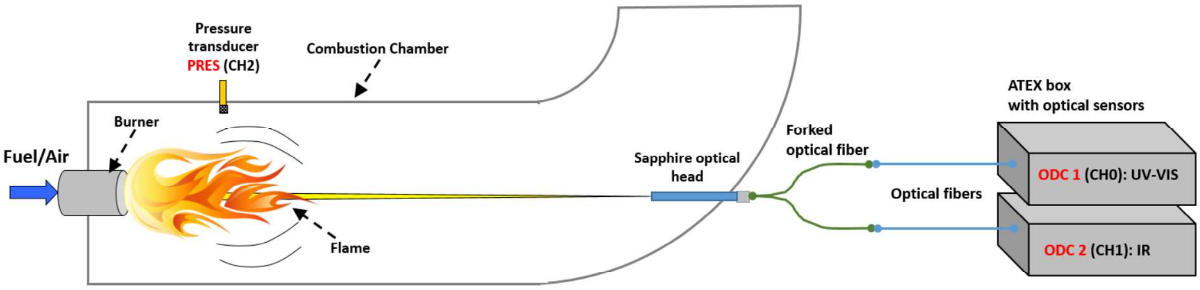

Figure 1. Sketch of the experimental set-up.

Experimental set-up

The two integral radiant energy signals related to the UV-VIS and NIR ranges are sampled by means of the ODC system developed and patented at ENEA [3-6]. ODC methodology lets to characterize in real time the dynamics of unstable conditions, chemical species, and temperature, and estimate the average flow speed.

The ODC system has an optical sapphire head with an angle of view of nearly 20 degrees, that samples radiant energy from a wide reacting region to capture eventual growing of instability precursors in different parts of the flame. The optical head is connected to two avalanche-photodiodes (APD) by means of a bifurcated optical fiber bundle (Fig. 1). The first APD works in the UV-VIS range (300-550 nm, coupled to a pass-band optical filter limiting the actual range to 320-550 nm) linked to the heat release fluctuations, H_R', and the second one in the NIR range (900-2600 nm, coupled to a high-pass optical filter) linked to the temperature fluctuations, T'.

The industrial burner investigated in this work has a central swirled premixed burner and a pilot coaxial burner, operated at 60 kW_t, ambient pressure, and fed with a mixture of natural gas (94.6/0.5/4.2/0.6 %vol. of $CH_4/C_3H_8/C_2H_6/N_2$) and air.

Combustion dynamics characterization

The burner consists of a pilot and a premixed module; the combustion and cooling air mass flow rates are constant during operation; the total fuel mass flow rate is also constant (nominal equivalence ratio ~0.56), split between the two modules (see black curve in Fig. 2). The flame switches from stable to unstable mode by increasing the premixed contribution. Figure 2 shows the time evolution of radiant energy and pressure raw signals (the ODC almost always identifies the same frequency peaks detected by the pressure transducer). Five time-windows (from A to E), each of 1 s, were examined as representative of different operating conditions (thermoacoustic instability conditions are reached in B and E). Figure 3 shows the history of the pressure peak amplitude in two frequency ranges, [0-320] Hz and (320-4.000] Hz, evidencing two unstable conditions exhibiting the greatest acoustic emission.

Three ramping up/down cycles are operated in ~8000 s: the energy provided to the system is constant (fuel flow rate). The first has a slow 40-100% premix split ramp in ~2000 s, visible in the ODC UV-VIS signal all over the time, but only at the peak unstable condition (100% split) in the NIR (likely due to the inertia of the combustor walls); the fast ramping down in ~500 s is visible in both signals. The second cycle has a ramp 0-80% premix split in ~700 s, turns quickly to 60% for ~1250 s, then to 0% very quickly; no instabilities are exhibited due to the system thermal inertia, i.e., they are prevented by the hotter condition: the energy provided through the fuel is constant but much lower than that stored by the combustor walls during the previous unstable condition and slowly released, as evidenced by both monotonically decreasing ODC radiant energy signals. The third cycle has a ramp 0-100% premix split in ~1500 s (faster than in the first cycle), then turns back to 0% very quickly; after the second cycle the temperature of the combustor walls lowered although it is likely higher than at the start of the first cycle: hence, the system exhibits an unstable condition seen by both ODC radiant energy signals, especially by NIR.

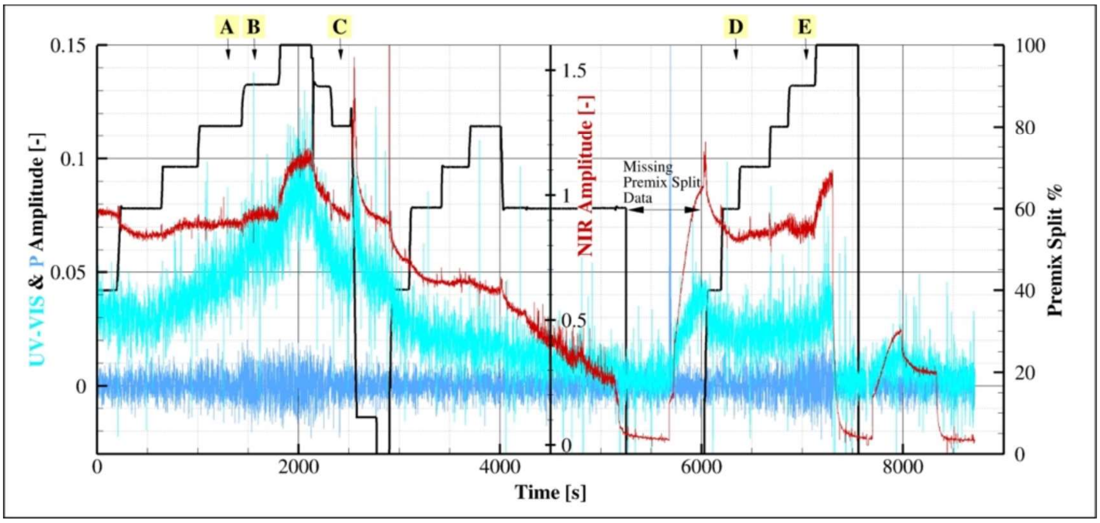

Figure 2. Time-history of the ODC optical signals in the UV-VIS (heaven, left axis) and NIR (red, central axis) ranges, and of the pressure signal (blue, left axis).

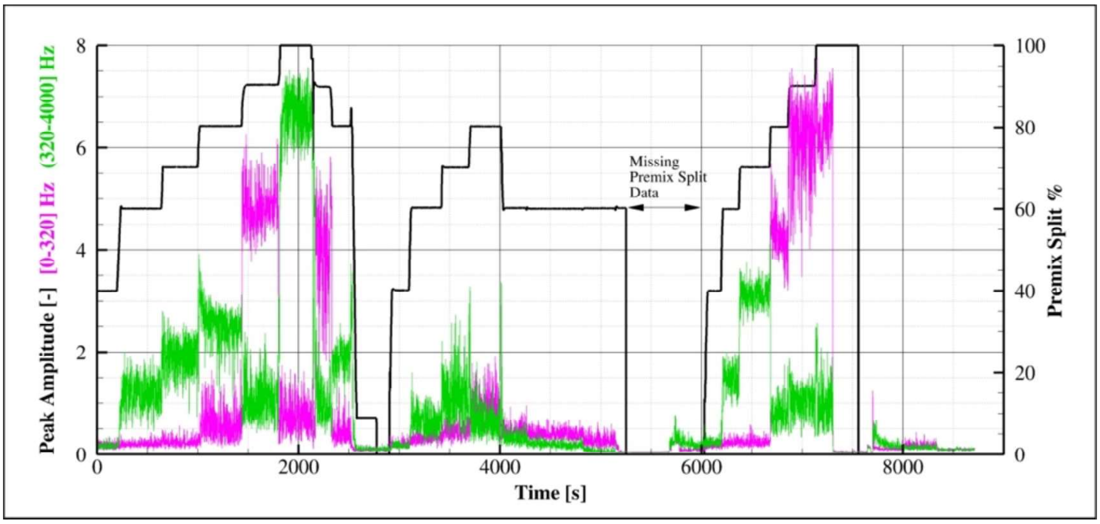

Figure 3. Time-history of the amplitude of the pressure peak in the frequency ranges 0-320 Hz (fuchsia) and 320-4000 Hz (green).

The *cross-correlation indexes* T'-H_R', p'-H_R' and p'-T', shown in in Fig. 4, are remarkably sensitive in all cases; the cross-correlation index between the ODC NIR optical signal and the pressure signal, i.e., p'-T', performs better than the others, reaching values between 0.5 and 0.65. The indexes T'-H_R' and p'-H_R' look very similar: this could imply that T' and p' are interchangeable; besides, the lower performance could be justified by the low signal to noise ratio observed for the UV-VIS contribution, H_R'.

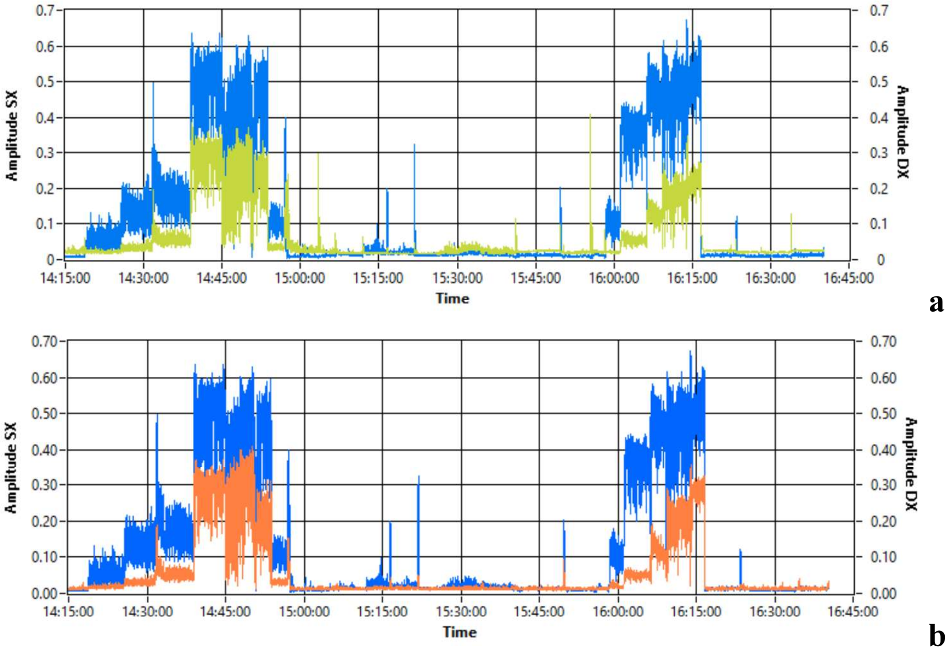

Figure 4. Time-history of the cross-correlation indexes between the ODC signals in the UV-VIS and NIR ranges (light green), the ODC NIR and pressure signals (blue), and the ODC UV-VIS and the pressure signals (orange).

Conclusions and future work

Sampling flame radiant energy using a photodiode and employing cross-correlation indices has shown promise as a practical method for monitoring the dynamic state of combustion systems and identifying thermoacoustic instability conditions in real-time. This strategy also has the potential to reduce monitoring hardware by substituting the flame detector with a robust optical sapphire head.

Future work will aim to enhance the optical signal sampled in the UV-VIS range by reducing the number of junctions between optical fibers and utilizing a more sensitive GaP (Gallium Phosphide) optical sensor operating in the 150-550 nm range. With these new features, the performance of the cross-correlation indices will be reassessed to determine whether combustion instabilities can be detected solely using the ODC system, focusing on monitoring the T'-H_R' index.

Acknowledgments

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