Innovative tools for investigation on flame dynamics by means of fast imaging

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***Abstract*—Computer vision and image processing are increasingly being used as investigative tools in various fields of science. Compared to other types of measurement techniques, image processing of high-speed camera shooting allows to obtain semi-quantitative information on dynamic aspects of the phenomenon under investigation. Combustion, both for propulsion and for energy production, is characterized by very fast phenomena that cannot be revealed by the typical measurement techniques used in test rigs for the development of prototypes. These dynamic phenomena, often called flame dynamics or flame instability, heavily affect the performance of modern combustors and their study has become essential, not only for the scientific knowledge of the phenomena, but also for the development of new combustion techniques. Therefore, for more than twenty years, the scientific community has been using fast imaging techniques to reveal phenomena that occur during combustion and this has allowed us to deepen our knowledge of the complex phenomena related to combustion itself. This paper describes the use of fast imaging and image processing techniques for the investigation of flame instability phenomena generated by gas turbine burners in an atmospheric test rig where a full-scale burner is tested. Optical investigations are conducted in the visible region of the electromagnetic spectrum.**

***Keywords*—computer vision, high-speed imaging, image processing, combustion science and technology, flame dynamics**

I. Introduction

Nowadays, the increasing awareness of the need to decarbonise the economy has put pressure on the power generation sector to reduce their share of CO_2 emissions. In this context, gas turbines (GTs) are the most robust, mature, and cost-effective technology especially for large-scale power generation. A convenient approach to achieve decarbonisation when using gas turbines, is to mix natural gas with increasing amounts of hydrogen [1]. However, hydrogen has several important physical and chemical properties that affect its use as a fuel and its use requires appropriate development and testing on prototype burners. Among these properties is the high reactivity of hydrogen that generates instability phenomena inside the combustion chamber; these phenomena manifest themselves in various forms: pressure fluctuations, heat and radiation release fluctuations, temperature fluctuations. The oscillations of these thermal and mechanical quantities are actually related to each other, Fig. 1, according a positive loop gain around a closed loop of cause and effect. A pressure oscillation is nothing more than a noise or sound and actually during pressure oscillation regime acoustic waves are generated by the flame and can be perceived by the human ear. In most cases of practical interest, it can be observed that this pressure fluctuation is characterized by the presence of well-determined frequencies depending on the aerodynamic characteristics of the burner and / or on the geometry of the combustion chamber.

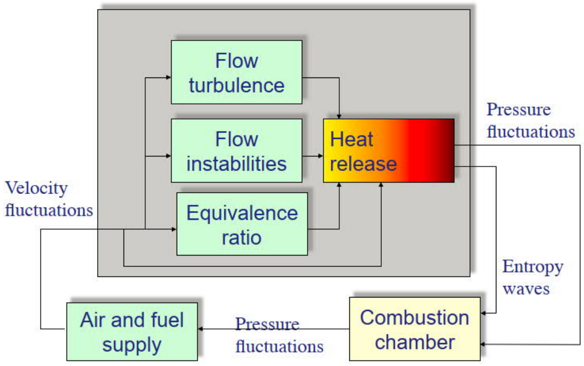

Fig. 1: Flame dynamics interaction in gas turbine combustor [2]

Fig. 2 shows the spectrum recorded during the experimentation of a gas turbine burner at the Laboratories of the Centro Combustione Ambiente. A main oscillation mode at 40 Hz and a secondary mode at about 950 Hz can be observed. These pressure oscillation modes during combustion tests were measured with a piezoelectric dynamic pressure transducer.

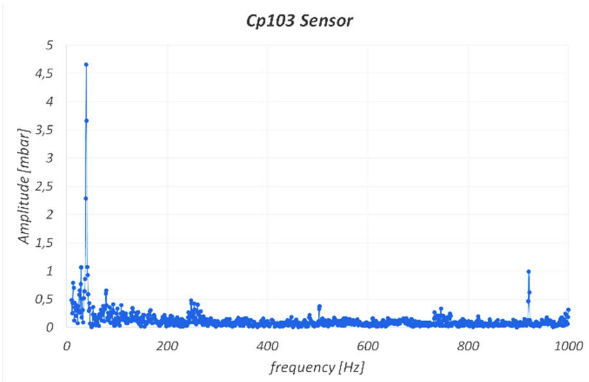

Fig. 2: Typical flame instability spectrum collected by piezoelectric transducer

Flame instability phenomena represent a considerable danger to gas turbines and their effects can be detrimental also leading to the destruction of important parts of the gas turbine, Fig. 3.

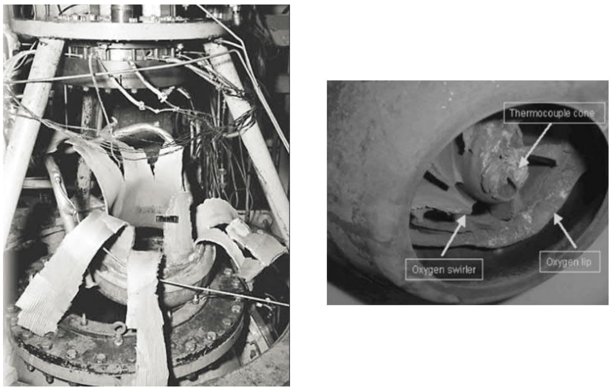

Fig. 3: Left: liquid rocket engine after high frequencies instability. Right: swirled burner after flash back occurrence

In order to support studies on flame instability, techniques based on fast digital cameras acquisition and image processing have been developed. Some of these approaches use high speed infrared cameras, [4] and [5]; these types of cameras are very sophisticated tools, but they show important limitations: firstly, their cost is extremely high and their use in industrial environments is not recommended, even if for research purposes. This type of cameras requires special lenses that are transparent to infrared radiation and germanium is used as a material. Germanium's transmission properties are highly temperature sensitive; in fact, the absorption becomes so large that germanium is nearly opaque at 100 °C and completely non-transmissive at 200 °C: paradoxically they are not ideal for combustion measures as they cannot be exposed to the radiation of flames for a long time.

In other approach, [6], a standard speed camera (50-60 fps) is used in conjunction with photodiodes or other optoelectronic devices. This type of methodology actually uses image processing for presentation purposes only and not for measurement.

In other studies, [7] and [10], methodologies similar to that presented in this paper have been applied to laboratory scale burners and not to full scale burners; moreover, segmentation operations are necessary before proceeding with the calculation of the frequency spectra generated by flame instability.

An interesting methodology on flame dynamics investigations is presented in [8]: here the chemiluminescence radiation generated in the ultraviolet region is used. It is necessary to resort to the use of expensive UV intensifiers.

Other approaches, [9], use image processing to predict the occurrence of instability phenomena through the application of neural networks.

A very comprehensive investigation on flame dynamics using fast digital cameras can be found in [11]. Here several technologies are compared: High-Speed OH Planar Laser-Induced Fluorescence, High Speed Stereoscopic Particle Image Velocimetry, UV chemiluminescence. The complete and complex methodology requires high level skills and can hardly be applied to full scale test objects.

The present paper describes an investigation technique on flame instability phenomena that exploits the chemiluminescence generated by the combustion of gaseous fuels and the Authors propose this methodology as a tool for visualizing instability phenomena during combustion tests. Compared to the methodologies just mentioned, the one proposed by the Authors has many peculiarities: first of all, the hardware used is very cheap while allowing to obtain high performances such as the maximum frame rate, 1000 fps. This methodology does not require highly specialized personnel for the execution of the measures, as in the case of pLIF or other measures. By not resorting to the use of laser sources, the measurement area must not be restricted and the light paths must not be confined for safety reasons. The use of data processing from the acquired images is minimal, essentially limited to the calculation of FFT: this allows to maintain a physical understanding of what we are doing. The data processing is mostly done to optimize the presentation of the results following the calculation of the FFTs. The optics necessary for the application of this methodology are small, C-mount and this allows the use of small sight windows; therefore, the measurements can also be performed on high pressure test rigs and on full scale burners.

In the opinion of the Authors, these characteristics give the developed methodology an innovative character.

II. Flame radiation

It is common experience that human eyes can see flames: depending on fuel type and combustion regime (fuel-air ratio) flames show different colours from reddish flames to bright blue flames. Flames generate in gas turbines combustors are blue due to premix combustion mode and lean combustion regime. In the emission spectrum of a premixed methane air flame there are intense peaks generated by CH* and C_2* radicals in the 400-500 nm region of the electromagnetic spectrum. Chemiluminescence is the luminescence produced by chemical reactions that induce the transition of an electron from its ground state to an excited electronic state. When the excited molecule decays to the electronic ground state, chemiluminescence emission at different wavelengths occurs, from ultraviolet-visible to infrared radiation.

CH* and C_2* are intermediate combustion products and they can be used as markers of ongoing combustion reactions, [12]. These species, called radicals, have very short life and they are generated in an electronically excited states compared to ground state. Therefore, they reach the ground state emitting photons at 431nm, CH*, 450-550 nm band, C_2*. As already mentioned, due to combustion radical short mean life, CH* and C_2* chemiluminescence is used as an indicator of heat release. Therefore, the fluctuation of chemiluminescence of these radicals can be used as measure of fluctuation of heat release during combustion reactions, in other words as a measure of the flame instability.

III. Image Acquisition and Image Processing Methodologhy

The methodology proposed in this work consists of three phases: acquisition, data analysis and presentation of the results.

The image acquisition software has been developed in National Instruments LabVIEW environment using the NI Vision Acquisition Software (VAS) application. It also allows to set the gain, exposure time, frame rate of the camera. The data files consist of arrays of intensity values; having set a bit depth of 10, the intensity values have 1024 intervals, 2^10 bit. The image post-processing software has been developed using the Visual Development module, VDM, also from National Instruments.

In the data acquisition phase, Fig. 4, the parameters for the best possible acquisition are set on the lens and camera, taking into consideration the range of frequencies to be investigated.

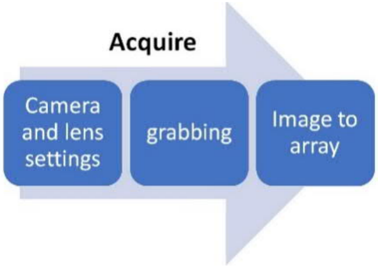

Fig. 4: images acquisition process

Frames grabbing follows; the images are not saved as such but converted into intensity arrays and this data is stored on disk.

The phase of analysis of the experimental data is rather articulated, as can be seen in Fig. 5.

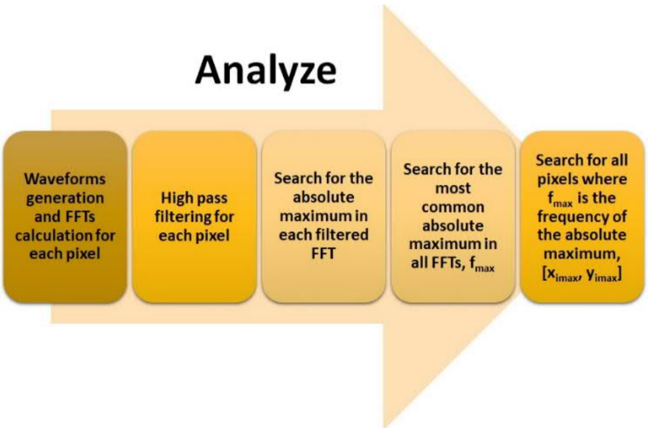

Fig. 5: the complex structure of the experimental data analysis phase

Let consider an image sensor with M x N pixels, Fig. 6, and a recorded sequence of L frames at t_0, t_1, ….t_L, with F_s the

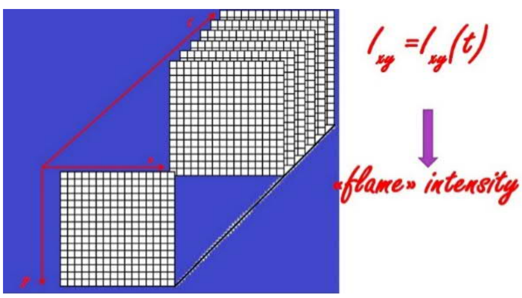

Fig. 6: Scheme of image sensor.

camera frame rate. Let consider pixel number xy in the array and be I_{xy} signal generated by the pixel: the sequence:

$$[I_{xy}(t_0), I_{xy}(t_1), I_{xy}(t_2), \ldots\ldots I_{xy}(t_L)]$$

is the time discrete measurement of the intensity produced by the shot object (flame) during the recording interval [t_0, t_L]: this is the waveform generation in Fig. 5. We are interested to measure flames instabilities that are generated by oscillation of heat release: calculation of FFT of the sequences

$$[I_{xy}(t_0), I_{xy}(t_1), I_{xy}(t_2), \ldots\ldots I_{xy}(t_L)]$$

will provide the spectral content of the heat release in the point recorded by xy pixel of the camera: this is the FFT calculation in Fig. 5. For the purposes of this methodology, knowledge of the DC value of the signal is not concerned, therefore a high pass filtering is applied. The cut-off frequency is decided by the experimenter's experience.

Subsequently, for each pixel the absolute maximum of the filtered spectrum is searched and the corresponding frequency is recorded; then the analysis software calculates the most recurrent frequency of the absolute maxima on all pixels. This is a decision-making process that informs the user about the frequency of the main oscillatory mode, f_{max} in Fig. 5

The main objective that this methodology intends to achieve is to give the experimenter information on the distribution of the flame instability modes through a two-dimensional map: It is the results presentation phase that deals with this task, Fig. 7.

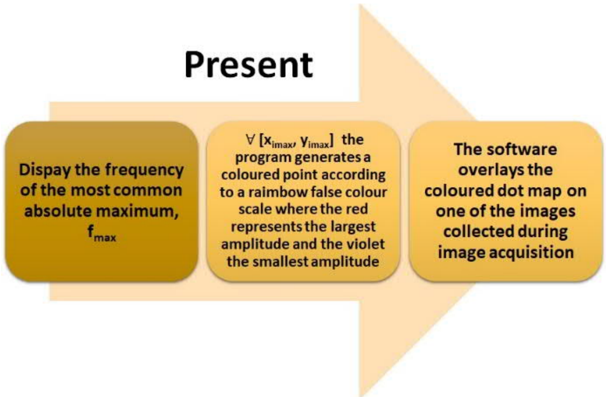

Fig. 7: procedures for results presentation

This map, for a given frequency f_{max} of oscillation of the light intensity, must inform about the "planar" distribution of the points in terms of intensity $A_{xy}(f_{max})$. This objective is achieved by points on a false colour scale, where red represents the greater intensities and violet the lower ones.

Furthermore, to increase the understanding of the measurement, the false colour map is superimposed on one of the real images recorded, through an overlay process. This procedure allows an easier interpretation of the phenomenon under observation and an immediate localization of the points with the highest amplitude of oscillation.

In Fig. 8 is shown the amplitude map for 50 Hz oscillating mode; this case was obtained during the development of the methodology on a laboratory scale burner having a power of 30 kW and fuelled by methane. Camera settings were: 1000 fps, 500 samples grabbed. The overlapping of the false colour point map with any of the collected images allows the localization on the test object of the distribution of the oscillation amplitudes at 50 Hz; the flame at the burner outlet is clearly visible.

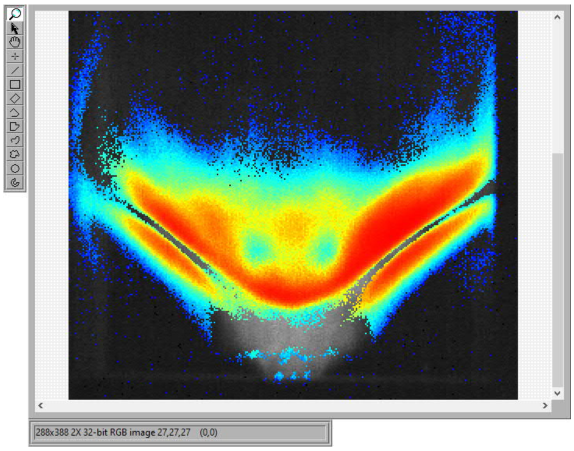

Fig. 8: 50Hz mode amplitude distribution in a test case applied to 30 kW laboratory scale burner

IV. TEST RIG SETUP

A. Atmospheric Combustion Facility

The tests have been performed in an atmospheric pressure, single burner combustion test rig with a full-scale prototype gas turbine burner. The test rig, Fig. 9, consists of a plenum chamber upstream of a double swirl-inducing burner and a combustion chamber downstream of the burner.

Fig. 9 Atmospheric burner test rig and cooled window for camera installation

The squared combustion chamber consists of an air cooled double walled metal liner with thermal barrier coating. Combustion air is electrically preheated, fed into a plenum chamber, and flows from here through the burner and the combustion chamber. The exhaust system is an air-cooled tube with the same cross section as the combustion chamber to avoid acoustic reflections at area discontinuities. The acoustic boundary conditions of the exhaust system can be adjusted from almost anechoic reflection coefficient to open end reflection by means of suitably dimensioned orifice plates. The burner can be fed with gaseous mixtures of natural gas and hydrogen and the maximum thermal input is 500 kW.

The test rig is equipped with two inspection windows on the bottom and on one side, Fig. 10, of the combustion chamber.

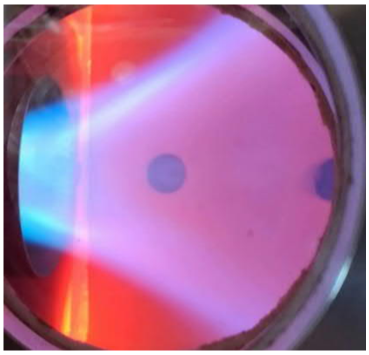

Fig. 10 High temperature sight glass window

B. Optic setup

For developing this Project, a low cost Ximea USB3 model MQ013MG-ON camera has been used, but the software part of methodology can be used with every data file recorded by a b/w camera. The camera is equipped with Onsemi Python 1300 NOIP1SN1300A-QDI CMOS image sensor.

Since Authors intend to use the camera as an instrument for measuring the light intensity, a bit depth of 10 has been set. Fig. 11 shows the quantum efficiency of the image sensor, black curve for B/W sensor, [13]. It can be observed that at 430 nm the quantum efficiency is acceptable, greater than 42%. However, at wavelengths greater than 700 nm the quantum efficiency is equal to the value at 430 nm, and in any case not negligible.

The purpose of the acquisition is to capture the flame images at 430 nm; inevitably, however, since the flames are confined to the combustion chamber, the image sensor will also be exposed to the walls of the combustion chamber which is in thermal equilibrium with the flame; therefore, the walls will be incandescent emitting black body radiation. During the experimentation in this test rig the flame typically reaches values of 1800-1900 K, therefore it is to be expected that the TBC layer on the combustion chamber also reaches this value.

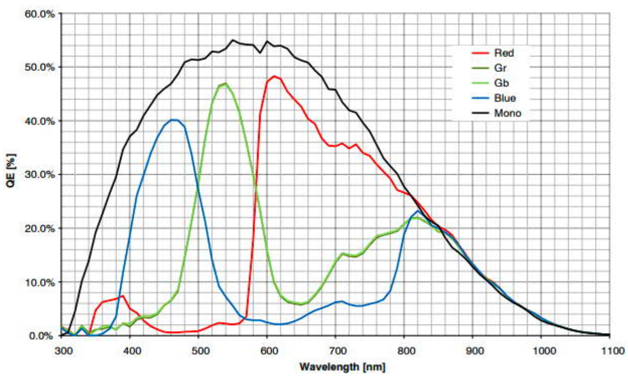

Fig. 11 Quantum efficiency of the camera image sensor

In Fig. 12 it is shown the spectral radiance of a black body at 1900 K is shown: as an example, it can be observed that in the 650-850 nm range, the spectral radiance increases by 2 orders of magnitude.

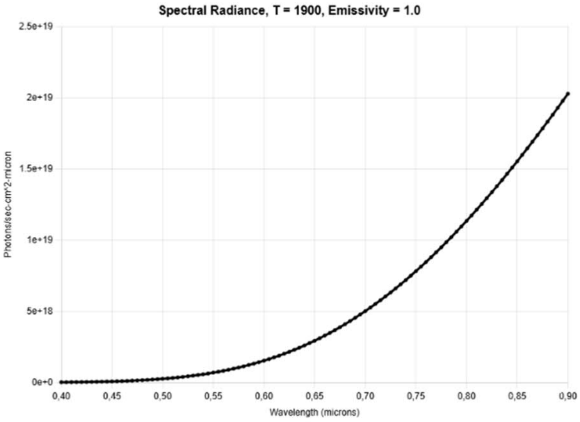

Fig. 12

In this same range, the reduction in quantum efficiency of the image sensor is about 35%. It is therefore to be expected that the black body radiation emitted by the walls could have two effects: overwhelm the chemiluminescence radiation of the flame and also bring the image sensor to saturation. These considerations lead us to think that the reduction of the exposure time of the camera or the adoption of a neutral density filter does not allow flame discrimination: it is necessary to proceed with a spectral discrimination. For the reasons just explained, the camera is equipped with an IR Cut-Off Filter during the measurements.

V. RESULTS AND DISCUSSION

The methodology proposed in this paper has been used in numerous test campaigns on full-scale gas turbine burners. During the experiments one or more piezoelectric dynamic pressure sensors were installed on the test rig to measure pressure fluctuations. It was found that in the presence of flame instability the dynamic pressure sensors and the developed optical methodology provided the same values in terms of oscillation frequency.

Some examples of the application of this methodology are provided below, with comments to highlight the advantages of this analysis.

Fig. 13 shows the stability analysis conducted on a class F gas turbine burner, during atmospheric test campaign. The thermal power generated by the burner during the tests has been 2 MW.

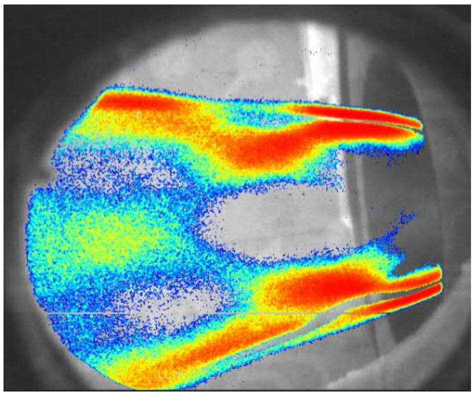

Fig. 13 Stability analysis of F class gas turbine burner at main oscillating mode, 91 Hz

The frequency of the flame instability was 91 Hz. It is interesting to note that the analysis provides values of the amplitudes of the vibration mode only in the points where the flame is located. Metal parts, such as the tip of the burner, visible in the figure, or ceramic parts, such as the lining of the combustion chamber, do not have variable amplitudes of light intensity. Although both the burner tip and the ceramic coating are incandescent and therefore emit visible radiation, their thermal inertia prevents them from oscillating at the same frequencies as the flame.

From the same figure it can be noted the absence of oscillations of the light intensity in the center of the flame. This phenomenon is due to the fact that the burner has an air-cooling line on its axis, and therefore in the vicinity of the flame axis there are no combustion reactions due to the presence of this cooling air.

Fig. 14 shows the stability analysis conducted on a class E gas turbine burner, during atmospheric test campaign at power output of 400 kW. In this case the camera has been installed in order to have a front view of the burner and not side view, as in Figure 13. In general, in this type of experimental combustion campaigns it is preferred to have at least the lateral view: this allows to evaluate some parameters such as the shape of the flame, for example open flame or closed flame, or the degree of attachment of the flame to the burner. In fact, as can be deduced from the figure, this information is completely lost when using a side view; however, it is interesting to note how the frequency analysis shows the effect of the swirler on the frequency oscillations.

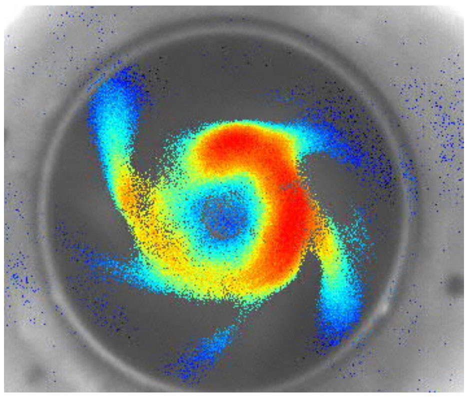

Fig. 14 Stability analysis of E class gas turbine burner at main oscillating mode, 160 Hz

Fig. 15 shows the stability analysis conducted on a class H gas turbine burner, during atmospheric test campaign.

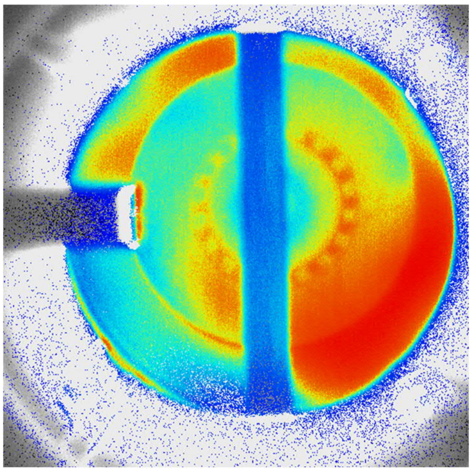

Fig. 15 Stability analysis of H class gas turbine burner at main oscillating mode, 71 Hz

In this experiment, a periodic flame instability at 71 Hz was observed; but through the piezoelectric dynamic pressure sensors the first harmonic of this frequency was recorded, at 142 Hz, of not negligible amplitude. Applying the proposed methodology, the presence of amplitude peaks at 142 Hz was found, Fig. 16. It is possible to notice that the non-uniformity of the planar distribution of the false colour points is similar for the fundamental and harmonic mode.

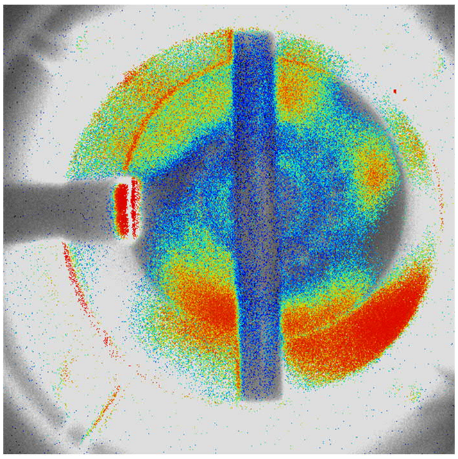

Fig. 16 Stability analysis of F class gas turbine burner at the second harmonic mode, 142 Hz

VI. CONCLUSION

In this paper a methodology applied to flame instability investigation on experimental gas turbine burners has been presented. The methodology is based on computer vision and image processing techniques. This methodology allows to detect flame oscillation phenomena at high frequencies and provides the experimenter with a "map" of the flame dynamics generated by combustion.

The methodology was developed with the aim of achieving the following characteristics:

1. cheapness of the hardware used
2. simplicity of measurement operations
3. possibility of application on full scale test objects at full pressure.

It emerged from the development of the methodology that the application of image processing under realistic gas turbine conditions provides a deeper knowledge of combustion phenomena and it allows the development and optimization of gas turbine combustors.

Some applications of the methodology applied to full-scale combustors of prototypes under development have been shown. The results obtained have been compared with traditional measurements obtained from dynamic pressure sensors.

REFERENCES

[1] M. Bothien, A. Ciani, J. Wood, G. Fruechtel, “Toward Decarbonized Power Generation With Gas Turbines by Using Sequential Combustion for Burning Hydrogen”, Journal of Engineering for Gas Turbines and Power 141(12):121013-1-10, 2019.

[2] S. Candel, D. Durox, T. Schuller, “Combustion dynamics Lecture 1a, Centrale Supélec”, Ecole Centrale Paris, EM2C lab, CNRS Université Paris-Saclay, 2016.

[3] S. Goers et al. (2014), “Endoscopic Chemiluminescence Measurements as a Robust Experimental Tool in High-Pressure Gas Turbine Combustion Tests”, ASME Journal (GT2014-26977), 2014.

[4] C. Allouis, A. Ferrante, G. Molfetta, “Identification and mapping of early thermoacoustic phenomena in gas turbine test rig”, 12th Quantitative InfraRed Thermography Conference, QIRT 2014.

[5] Albert Chang Her Jie et al., “Flame analysis using image processing Flame analysis using image processing techniques”, 2018 IOP Conf. Ser.: Mater. Sci. Eng. 342 012060.

[6] D. Sun, G. Lu, H. Zhou, Y. Yan and S. Liu, “Quantitative Assessment of Flame Stability Through Image Processing and Spectral Analysis”, in IEEE Transactions on Instrumentation and Measurement, vol. 64, no. 12, pp. 3323-3333, Dec. 2015.

[7] L. Xu, F. Li, J. Sun and Z. Cao, “Dynamic Characterization of Pulse Combustion by Image Series Processing”, in IEEE Sensors Journal, vol. 18, no. 23, pp. 9682-9690, Dec.1, 2018.

[8] A. Lay-Ekuakille et al., “Advanced imaging processing for extracting dynamic features of gas turbine combustion chamber”, Measurement, vol. 116, pp. 669-675, Nov. 2017.

[9] S. Sarkar, K. G. Lore and S. Sarkar, “Early detection of combustion instability by neural-symbolic analysis on hi-speed video”, Int. Conf. Cogn. Comput. Integr. Neural Symbolic Approaches, 2015.

[10] F. Y. Li and L. J. Xu, “An image processing approach for characterizing working frequency of pulse combustion”, IEEE Int. Conf. Imag. Syst, 2017.

[11] C. M. Arndt et at., “High Speed Imaging of Flame Structure and Dynamic Processed in Swirl Stabilized Prevaporized Liquid Fuel”, AIAA 2019-0732.

[12] F. Güthe, D. Guyot, G. Singla, N. Noiray and B. Schuermans, “Chemiluminescence as Diagnostic Tool in the Development of Gas Turbines”, Applied Physics B, Vol. 107, pp. 619-636, 2012.

[13] ON Semiconductor Corporation, “PYTHON 1.3/0.5/0.3 MegaPixels Global Shutter CMOS Image Sensors NOIP1SN1300A Manual”, 2021.