ANALYSIS OF A PULSED FLAME AT INTERMEDIATE PRESSURE

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ABSTRACT : *Our research focuses on the development of sensing techniques regarding monitoring of gas turbine combustion stability.*
This paper describes a method for the visualisation of fluctuating density regions within a pulsed swirl stabilized flame (CH4-Air) of a gas turbine test burner at intermediate pressure.
The burner was designed for a thermal power of 70kW. It includes optical access for non intrusive measurement devices. An air pulsator sets at a whished frequency a flow instability in the main air feed. The acoustic natural modes of the setup are detected with a microphone.
Supporting measurement techniques such as particle image velocimetry and laser vibrometry are used. The measurements are time- or phase-resolved.
This paper is a joint-study of TU Graz and ONERA.

1 Introduction

The present work applies a laser vibrometer (LV) to monitor combustion instabilities in gas turbine combustors. It discusses more specifically the mapping of coherent structures involved in thermoacoustic couplings. Combustion instabilities can cause strong heat release fluctuation and thus performance degradation, as well as the induced periodic motion of the flame front can damage the assembly injection system – flame tube. Current research focuses on lean injection systems due to environmental policies. For instance LPP injectors (Lean Prevapourised Premixed) suffer from combustion instabilities, so that control strategies of the injection system are needed. Our motivation is to detect and analyse local and temporal density fluctuations ρ' in the combustion zone for further control strategies.
LV has proven to detect with high sensitivity coherent structures in a turbulent flow (Mayrhofer 2001 [1] and Hampel 2006 [2]) as well as combustion instabilities at ambient conditions (Giuliani et al. [3]).
This paper describes the test rig for analysis of premixed air-methane combustion at intermediate pressure. The setup was engineered at TU Graz. A modulation of the burner air flow is generated by a

siren, and the dynamics of the injection is observed with help of PIV. LV is dedicated to the analysis of the flame front dynamics at middle range frequencies, under pressure. Some aspects of the experimental conditions, LV data acquisition and processing are detailed. We describe why LV is capable of refined combustion instability detection because of its high spectral sensitivity, and establish its applicability in presence of optical accesses on a pulsed flame at intermediate pressure.

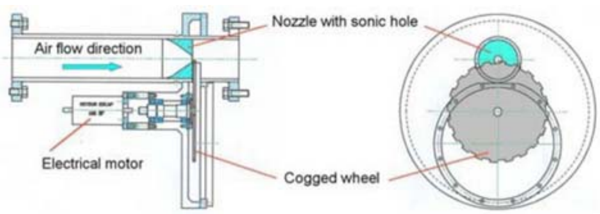

Fig. 1: ONERA siren for flow excitation

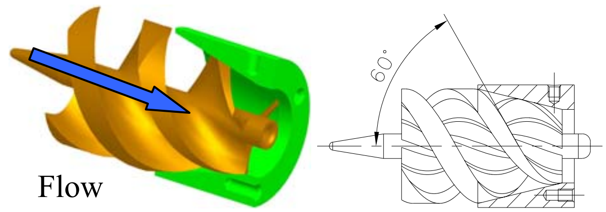

Fig. 2: Axial swirler with swirl angle 60° and Venturi tube; left: 3D-view; right: side view.

2 Experimental setup and operating conditions

The intermediate pressure single burner sector was fully developed at TU Graz. This burner provides a V-shaped premixed methane-air flame at pressures up to 2,5bar absolute under controlled inlet pulsed flow conditions.

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2.1 Resonator and siren

A siren provided by the ONERA [4, 5] is used as a flow exciter (Fig. 1) to assure controlled pulsed inlet conditions for the burner. It consists basically in a choked throttle, in the front of which a toothed wheel is rotating at a wished frequency. The periodic blockage due to the passage of a tooth generates the pulsation. A latest improvement on this system is the use of a high-precision Maxon ECmax30 motor, including an encoder HEDL 5540 providing 500 pulses per revolution as reference signal. In addition an EPOS 24/5 control unit is used to ensure maximum accuracy by assessing the pulsation frequency. With this configuration a maximum aberration of $\pm 0.2\%$ at $540 Hz$ can be assured.
A 3,3m long supply pipe allows setting the pulsation. At atmospheric conditions, when the combustor casing is dismounted so that the injector is in free-jet, the pipe works as a quarter wave resonator provided that the injector is acoustically transparent. The resonant modes can be amplified by the siren mounted upstream of the burner air (or main air) supply pipe.
The pressure oscillation generated by the siren is surveyed by a microphone model PCB-106B50 connected to an amplifier type 482A22. The microphone is plugged 2m downstream of the siren, mounted on a lyre to protect the instrument from conductive heat transfer.

2.2 Burner for intermediate pressure

The test rig burner is a downscale of the laboratory injector designed by Giuliani and Wagner and presented in [6], for combustion at room conditions. Methane is injected about 0,63m upstream the burner to ensure total premixing. The CH4-Air mixture is then injected in the primary zone via a swirler to vortex-stabilise the flame. We used an axial swirler combined with a Venturi nozzle (Fig. 2). The axial configuration was chosen to keep the swirler as acoustical transparent as possible at the cost of a lower swirl number ($S = 1{,}1$). The Venturi is used to keep the flame away from the front plate and to prevent flash-back.

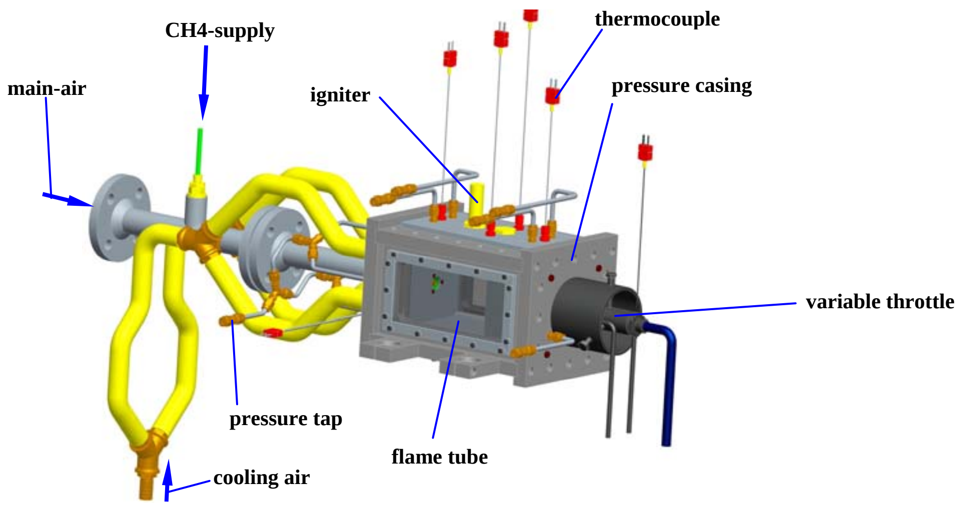

Fig. 3: Intermediate pressure combustor with air and methane supplies, variable throttle, instrumentation and optical accesses.

The combustor itself is a dump-design with a flame tube embedded in a pressure casing (Fig. 3). The cooling-air-feed is injected via four separate hoses and can be regulated separately from the main airflow. Fig. 5 offers a cut of the combustor, as well as the resulting flame aspect at 2bar.
The pressure casing and the flame tube have optical accesses for laser based measurement techniques. The windows are cooled by the cooling-air-feed only. No cooling holes are present on the liner along the primary zone. Both liner and pressure casing windows use Robax® glass with a thickness of 4mm, able to withstand temperatures up to 700°C. For the pressure casing double layer windows are used. As a consequence, any line of sight measurement undergoes 12 interfaces.
To assure operating conditions from ambient up to 2,5bar absolute, a variable air-cooled throttle at the combustor exit is deployed.

2.4 Operating conditions

The general measurement setup is reported in Tab. 1. The operating conditions for the PIV (part load, isothermal, describing the injection aerodynamics at ignition conditions) and LV measurements (full load, under combustion, intermediate pressure) are reported in Tab. 2 and Tab. 3 respectively. We study lean combustion. However the equivalence ratio must not be too low due to the risk of flame blow-out when being pulsed. At operating conditions, we estimate the equivalence ratio to vary in an interval [0,6-0,7] based on a heat balance model. The mass flow rates for burner air, cooling air and methane are known, as well as the outlet temperature. The adiabatic flame temperature is computed as a function of the fraction of cooling air recirculated within the primary zone, with help of the thermochemistry model GASEQ [7]. The outlet temperature results from the mixing of burnt gases with the rest of cooling air, and is compared to the measured one. This process was applied to several operating points and involves an average participation of 25% of the cooling air in combustion.

For the experiment with flame under pressure, the flame is first ignited at low injection velocity and low methane injection, to avoid strong detonation at start-up with the risk to damage the windows. After that, the flame is progressively brought to a 25kW thermal power by augmenting progressively the main air, methane and cooling air flows. The flow rates are then kept constant so that the injection velocity is inversely proportional to the augmenting pressure ratio. To put the flame in a pressurised environment, the outlet nozzle is progressively throttled.

Configuration	
Supply pipe length	3,3m
Axial swirl angle	60°
Number of blades	3
Venturi ratio	½
Chamber Dimensions (Flame tube)	200x96,4x96,4 (L x W x H)
Chamber Dimensions (Casing)	230x120x120 (L x W x H)
Outlet nozzle diameter	21,6mm (fully opened)

Tab. 1: General measurement setup

Operating Conditions (PIV-Measurement, part load, isothermal)	
P and T_{inlet}	room conditions, 1bar, 300K
Air feed	2g/s
Axial inlet velocity	7,2m/s
Injector pressure loss	1,6%
Swirl number	1,1
Siren excitation range	0-2,4kHz, set at 33Hz
Stereo-PIV field of view	80x90mm
Angle between cameras	42°

Tab. 2: Operating conditions for PIV measurement

Operating Conditions (LV-full load, Measurement)			
P and T_{inlet} flame tube (front plate)	1,939bar, 554K	Axial inlet velocity	12,8m/s
P and T_{inlet} pressure casing (wall)	1,942bar, 331K	Injector pressure loss	1,6%
P and T_{out} flame tube (wall)	1,936bar, 596K	Flame pressure loss	0,9%
P and T_{out} pressure casing (wall)	1,934bar, 486K	Swirl number	1,1
Air feed (primary air)	6g/s	Max. T_{wall}	540K
Air feed (cooling air)	25g/s	Siren excitation frequency	540Hz
Methane feed	0,5g/s	T_{in} (fresh mixture)	285K
Equivalence ratio (25% estimated air recirculation in primary zone)	$\phi = 0{,}7$	T_{out} (exhaust gases)	1050K

Tab. 3: Operating conditions for LV measurement at approximately 2 bars in the combustor.

3 Measurement Techniques

3.1 Stereo PIV – 3-Dimensionnal Particle Image Velocimetry

3D PIV is used to establish the velocity flow field as well as observe the flow dynamics generated by the swirler. A stereo PIV measurement enables us to measure the 3D velocity components in the flame cross-section and to calculate the swirl number. The PIV optics consists of a Nd:YAG-Laser from New Wave GEMINI (532 nm, 120mJ/puls, pulse duration 3-5ns, 15Hz) and two DANTEC 80C60 HiSense cameras (1280x1024 pixels, 12 bit greyscale). The system is driven by a DANTEC FLOWMap 1500 PIV Processor. An aerosol of DEHS (Di-Ethyl-Hexyl-Sebacat, specific particle size 0.7-1µm) is used

as a tracer for isothermal characterisation. The DANTEC PIV software FlowManager v4.60.28 processes the raw data, and a more detailed analysis is performed with MATLAB routines.
As shown in Fig. 4 left, one camera is mounted perpendicularly to the light sheet. The cameras are positioned with an angle of 42°. Both cameras are equidistant to the light sheet plane (Fig. 4, right).
To enable phase-locked measurements, the PIV system is triggered via the siren, which delivers a TTL signal per flow pulsation cycle. A settable time-lag allows to perform several phase measurements within the pulsation period.

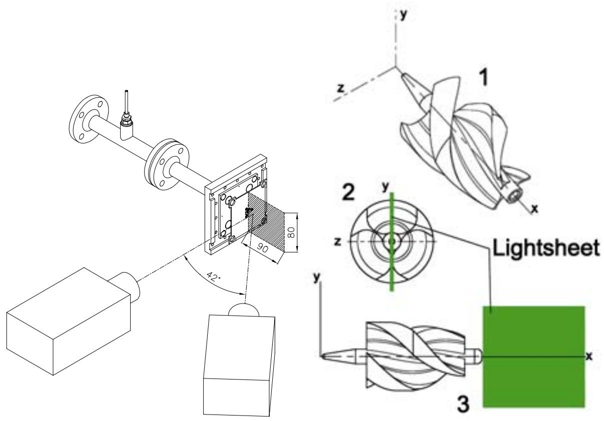

Fig. 4: PIV measurement setup; left: camera setup; right: 1. coordinate system, 2. front view, 3. side view

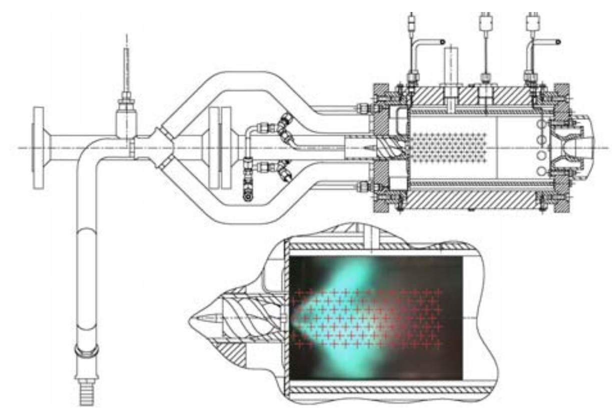

Fig. 5: LV setup (detail view: measurement points).

3.2 LV - Laser Vibrometry

Commonly LV is used to measure the vibration on surfaces. Its principle is based on interferometry. The line-of-sight interference pattern between a reference laser beam kept at constant optical path, and the object laser beam reflected by the surface of interest, will alternate from constructive to destructive interference provided the surface moves. In order to differentiate whether this surface moves forward or backward, the reference beam is shifted in frequency with the help of a Bragg cell. Any surface motion provokes a Doppler effect, and a frequency demodulation of the interferometer signal allows to quantify this motion in real-time.
By keeping the geometrical path of object laser beam constant, it is possible to detect density fluctuations in an isothermal jet, as Mayerhofer and Woisetschläger [1] showed. They describe how the LV output voltage u' is proportional to the time derivative of the density ρ' as follows:

$$u'_f = \frac{G}{k}\int_Z \frac{\partial \rho'_f}{\partial t}\,dz \qquad (1)$$

where G is the Gladstone-Dale factor, related to the refraction index of the medium, k is an instrument gain factor and Z the penetration length of the laser through the medium. Subscript f means phase averaged at a fixed frequency.
The measurement is performed along the line-of-sight, so that it integrates all changes of density along its path. In order to determine and quantify the precise density fluctuation, inversion methods such as an Abel transform are possible, provided the hypothesis of axisymmetry of the flow is effective.

The same method can be applied to density fluctuation related to the presence of a flame. Note that this technique is not adequate for quasi-static variations, since its electronics are set to observe rapid changes of the line-of-sight and Bragg-cell shifted interference, but it fits situations starting from a few Herz frequency fluctuations to the high frequency domain. The LV used is a model Polytech OVD 353.

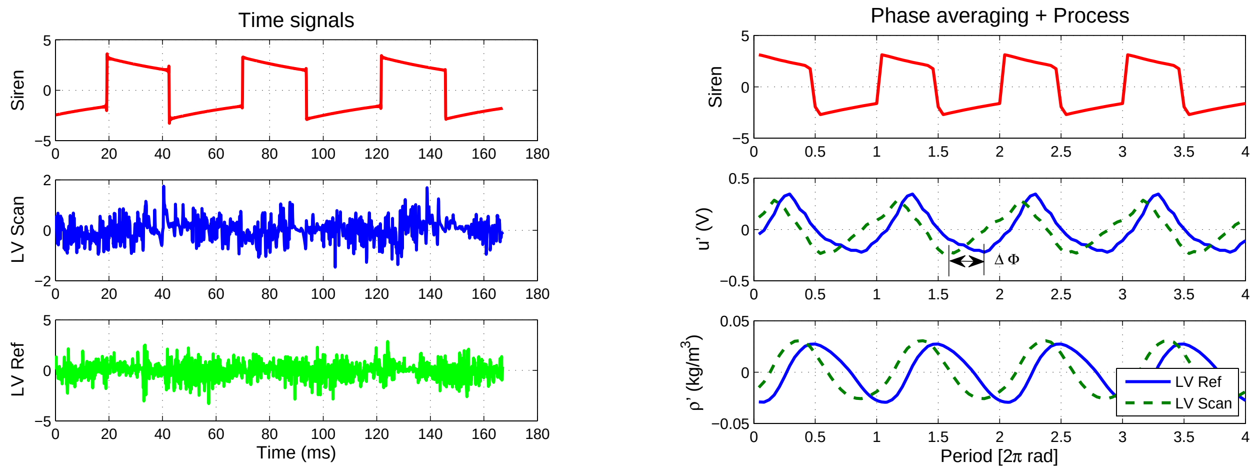

Fig. 6: Left: Time signal acquisition of the reference (siren). Right: LV signal, and phase-averaging post process.

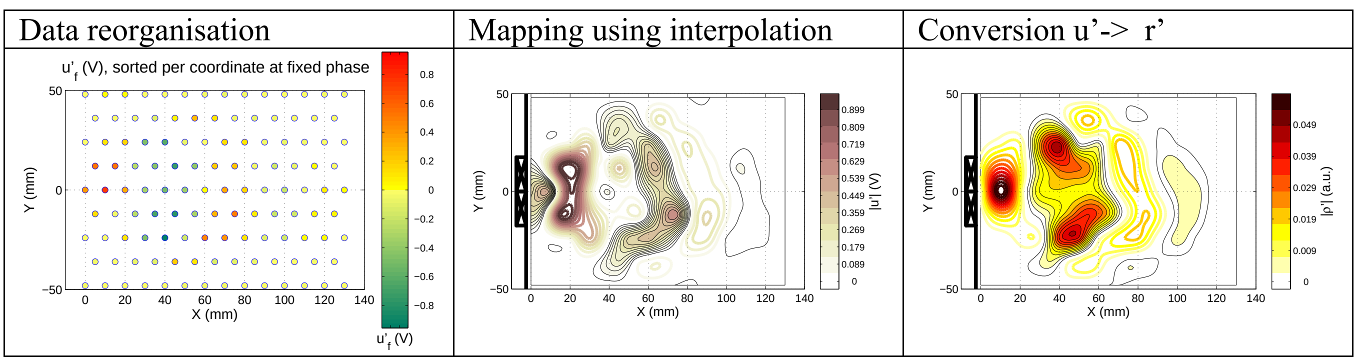

Fig. 7: Mapping process. Left: sorting of the measurements per grid point at a fixed phase. Middle: linear interpolation of uf'. Right: process of ρf' map. Full contours: positive fluctuation. Line contours: negative fluctuation.

By scanning in line of sight a measurement grid, it is possible with help of a synchronisation signal (siren TTL or microphone signal) to reconstruct the phase-defined field of density fluctuation. Fig. 5 displays the measurement grid.

The determination of the phase-defined voltage signal u' at frequency f is based on the correlation between the scanning LV time signal and a reference signal recorded simultaneously (a fixed LV, a microphone, or the siren TTL trigger signal per pulsation). In case forced pulsation is studied, the most precise method is to rely on the TTL signal generated by the siren, marking the beginning of each pulsation cycle and allowing a phase-averaging process as shown in Fig. 6. In that case, the phase-averaging post-process is realised with Matlab routines: the time signal is resampled over single pulsations periods, marked by an upward TTL front (Fig. 6, left). All subsamples are averaged to a resulting phase-average period signal u'_f (Fig. 6, right). Assuming a constant *GZ/k* factor, the line-of-sight density fluctuation ρ_f' is derived from u'_f based on an integration of Eq.1.

In case the natural resonance of the flame is studied (no siren excitation, therefore no siren TTL signal), a second instrument (fixed LV or microphone) is taken as a reference. The phase-shift $\Delta\phi$ between both signals (Fig. 6, left) is determined with help of a correlation analysis (see Giuliani et al. in [6] for details), and the amplitude of u'_f is measured in the amplitude spectrum of $u'(t)$.
The mapping method consists in reorganising all phase-defined quantities as a function of their coordinates (Fig. 7, left), sorted with an increasing phase angle over one pulsation period. A Matlab-patented smoothing interpolation (called 'v4') is used on the u_f' grid to provide a voltage map (figure Fig. 7, middle). The ρ_f' map computed with Eq.1 is represented in figure Fig. 7, right.
The time-resolved aspect of the measurement is the main quality of LV. The signal delivered by this instrument is physically related to the time derivative of the density ("velocity mode": $u'(t)=f(d\rho'(t)/dt)$), and not its absolute real-time value ("displacement mode", or integrated "velocity mode" over time: $u'(t)=f(\rho'(t))$. Therefore LV offers a constant high level of spectral sensitivity, with a better signal-to-noise ratio in the high frequency domain than classical time-resolved interferometric methods (e.g. using a photosensor in line-of-sight or high-speed CCD sensor if the whole interference pattern is analysed). Fig. 8 underlines this property, by comparing the spectrum of the real-time density status signal (LV "displacement mode" output voltage) with the time derivative one (LV in "velocity mode"). The "displacement" signal has the 1/f spectral sensitivity decay behaviour of many sensors, such as opto-sensors, microphones etc., whereas the "velocity" signal conserves a constant threshold noise. This is due to a property of the Fourier transform of a time derivative reminded in equation 2.

$$F\left(\frac{df(t)}{dt}\right) = i \cdot \omega \cdot F\big(f(t)\big) \tag{2}$$

Note also the difference in gain at the marked excitation frequency of 540Hz, to the advantage of the "velocity" mode. Hampel and Woisetschläger [2] crossed the beam of two laser vibrometers over a calibrated jet and developed a deconvolution method, allowing to isolate the turbulence observed at the cross point. As a result, dual laser vibrometry (DLV) is a potential candidate for detailed turbulence analysis in the high frequency domain.

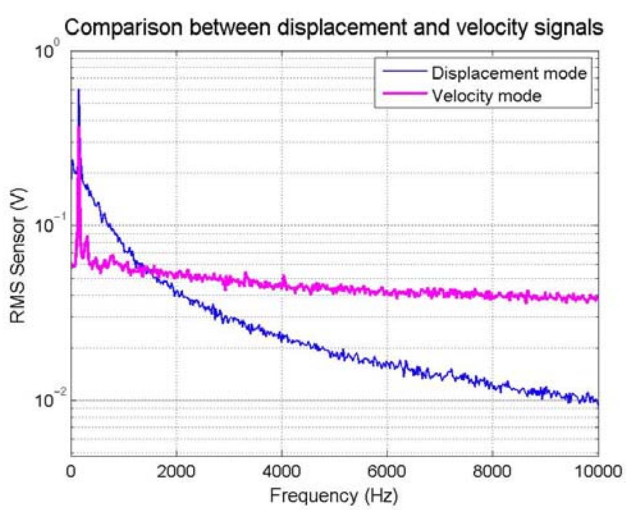

Fig. 8: Comparison between the displacement mode and the velocity mode

3.3 Automation of LV measurement

The LV measurement has been automated for a more convenient and faster procedure. The LV instrument is mounted on a Lightweight traversing system from Dantec. This is a 3-axis traversing system with an accuracy of 40 µm and is controlled via RS232 interface. National Instruments' LabVIEW 8.0 is used to automate the LV measurements. The graphical user interface of the software allows easy set-up of all parameters of the Dantec Lightweight traversing system as described in [8] (RS232 settings, traversing speed, limits, input-files, output-files) and adjustment of the Laser Vibrometer settings (velocity filter, tracking filter, velocity range, and displacement range). Once positioned at a given measurement point the software waits four seconds for the vibrations caused by the traversing to fade. The interface for data acquisition is a National Instrument PXI-1033 chassis. By default, data acquisition takes 10s (400.000 points @ 40kHz). The duration of a complete scan for a field of view of 40x100mm subdivided into 91 measurement points (7 rows à 13 points) is approximately 30min. In addition to the data acquisition of the Laser Vibrometer signal a normalised signal-to-noise-ratio is written to a separate file for each measurement point in terms of maximum, minimum, and mean value to analyse the measurement quality.
In post-process, a Matlab routine takes care of rearranging the data from coordinate-specific and time-resolved measurement to phase-averaged data on an interpolated map.

4 Results

4.1 PIV measurement

The pulse jet dynamics are studied with the help of PIV at isothermal conditions in free jet configuration (injector and front plate only, no pressure casing and liner). The chosen operating point is the minimum admissible velocity at start-up. The siren provokes a fluctuation of mass air flow resulting in a fluctuation of the swirl number. The jet swirl component behaves alternatively from weak to strong. As a result, the inner recirculation zone has a come-and-go motion. A ring vortex generates at the front plate, detaches and is transported by the flow. This aerodynamic has been described by Giuliani et al. [4], where the coupling with the flame structure is also discussed. In Fig. 10 the pulsed velocity field is represented as well as the related vortical structures. In order to underline the macroscopic aspect of the jet motion, a low frequency is chosen (33Hz). A set of four phase-conditioned pictures represent one pulsation period. For each measurement, 400 double phase-locked PIV-pictures were processed (200 per camera actually). On the vorticity maps, computed from the rotational of the air flowfield, the red structures are turning clockwise and the blue ones anti-clockwise. A ring vortex is materialised by both of these in the studied cross-section. One notices also on the maps a vortex pairing, where a vortex placed inside the jet cone is immediately followed by an outer vortex, contra-rotating. Panda et al. [9] have shown that the detached structures evolve at about half the reference flow velocity at injection. On these plots, we measure along the expansion cone of the jet V_{conv}/U_{ref}=0,3. Experience shows that the higher the frequency, the smaller the structures and the nearer the convection velocity to U_{ref}.

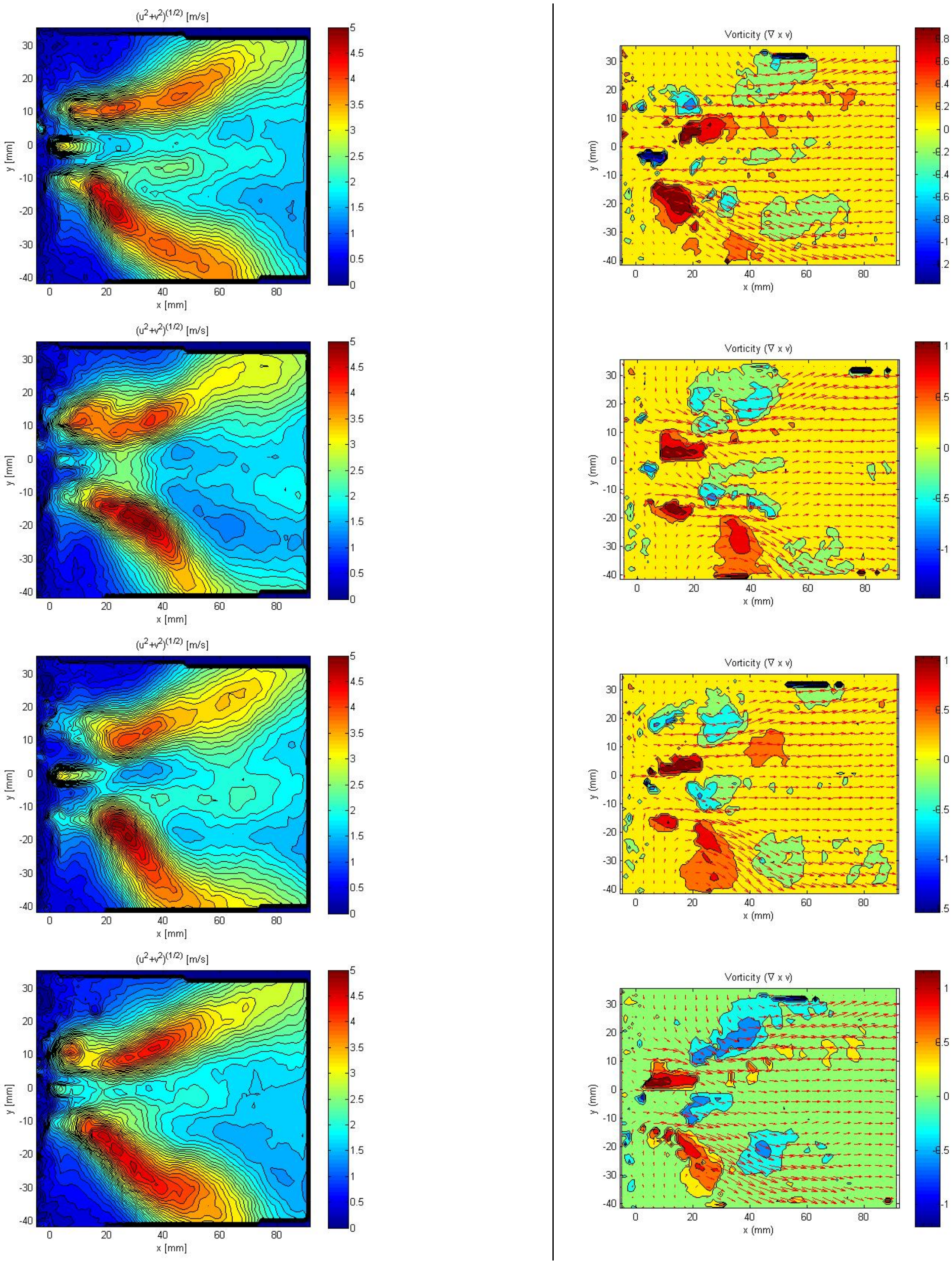

Fig. 9: Analysis of the pulsed jet dynamics (isothermal case, free jet - 4 phases 0, pi/2, pi and 3/4pi are representing one cycle of operation at 33Hz); left: normalized velocity; right: vortical field analysis, where the main structures are computed based on a rotational of the velocity field

In the following, we compare this jet aerodynamic with a situation in enclosed jet configuration, with combustion and at intermediate pressure. Since we did not perform PIV measurement under the same conditions, the direct comparison is not allowed. However, we report on the similarity of behaviour between PIV and LV performed in free-jet configuration on a different injector in reference [3]. This is the reason why we assume a similar jet dynamics in presence of a combustion chamber.

4.2 LV measurement

The atmospheric flame is rather elongated in comparison with the pressurised one, more compact, because of the difference in injection velocity.
Fig. 10 displays the density fluctuation at 540Hz in closed jet configuration at atmospheric condition (left) and at approximately 2bar (right) respectively. The change of compactness is the first observation between the two series. In both cases, the line of sight measurement displays an alternation of positive and negative density fluctuation, strongly related to the flow dynamics described by the PIV: these density fronts generate at the front plate, detach, and follow the flow. The convective velocity of the structures is also in the proximity of the half of the reference velocity at injection (with U_{ref}=27,1m/s, V_{conv}=11.9m/s is measured at atmospheric conditions and gives V_{conv}/U_{ref}=0,44; while at 2 bars: U_{ref}=*12,8*m/s, V_{conv}=8.1m/s it comes V_{conv}/U_{ref}=0,64).
The structures are clearly visible in the vicinity of the front plate. At atmospheric conditions, after x=50mm (which marks the swirl vortex breakdown), the structures are no more observable. This distance is reduced to 40mm in the pressurised case. The interaction with the walls is also of importance.

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5 Discussion

In order to perform precise LV measurements and thus quantify the local density, a particular care has to be brought to the optical setting. The main drawback of using windows is that each interface involves a reflection. The team at TU Graz works at the moment on estimating the measurement error on density fluctuation induced by the vibration of the windows. Provided, that the density is correctly measured, together with the acoustic pressure it is possible with the help of tomography to turn back to the local temperature and heat release fluctuations.
In previous contributions [6, 10], the ability of LV to detect natural resonances was pointed out, which is of great interest in terms of combustor testing, as well as in terms of thermoacoustics for fundamental research.
Including LV as an embarked measurement technique for real-time combustion monitoring is feasible but is a long-term issue. A lot of engineering regarding optic maintenance (vibrations, heat, focus, sensing drift, etc.) under repeated operation has to be done. Still, the state of the art methodology can be recommended for laboratory purpose as a supporting diagnostic method, or in the industry as a rapid testing method.

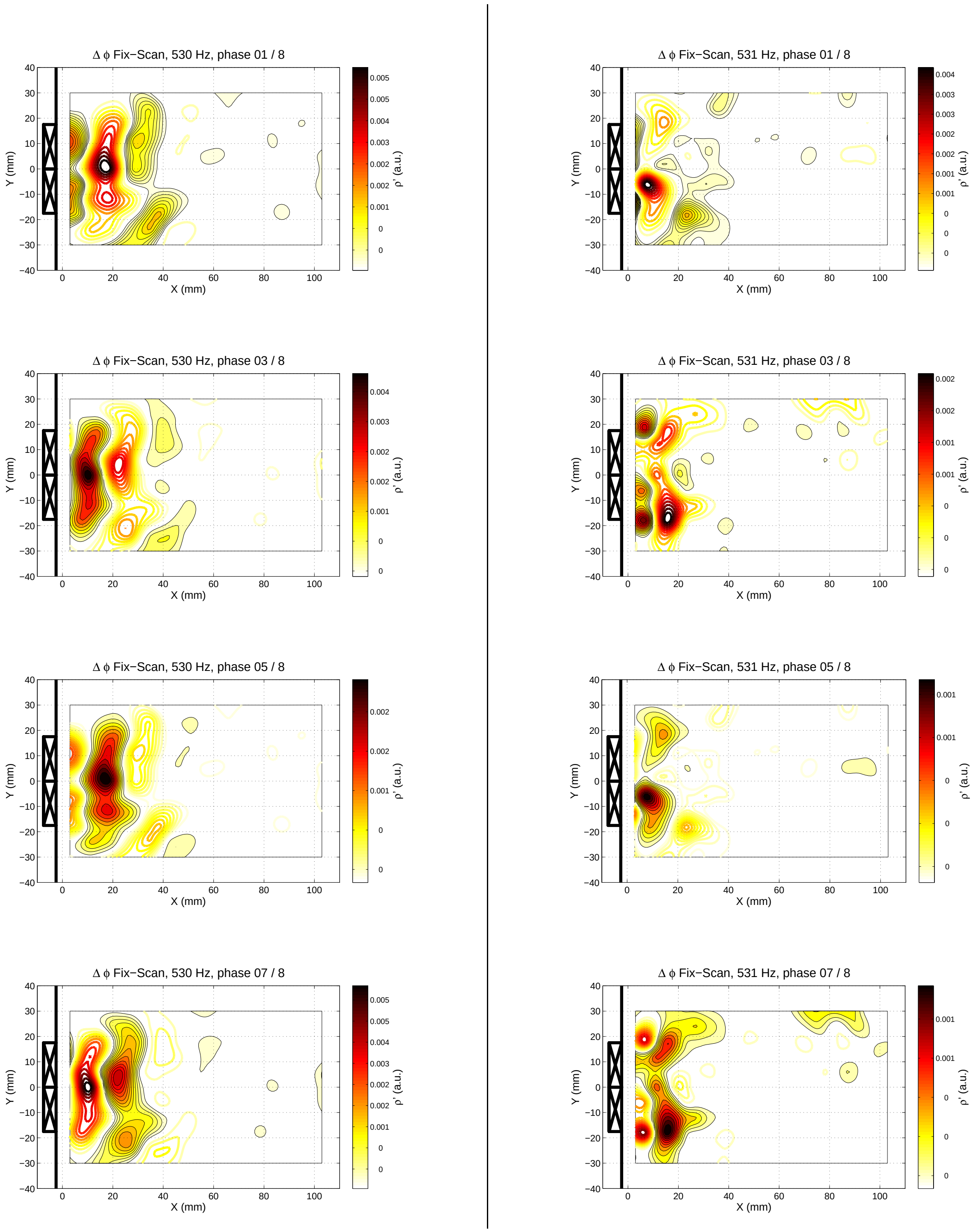

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Fig. 10: Density fluctuation measurement performed with LV on a pulsed flame in closed-jet conditions (pulsation frequency at 540Hz – 4 phases are represented at 0, pi/2, pi, 3/4pi), the filled contours represent a positive density fluctuation and the light contours negative ones, the color represents the intensity); left: atmospheric conditions, right: intermediate pressure at 2,0bar inside the combustor

6 Conclusions

Strong density fluctuation is a potential marker for the detection of the presence of a thermoacoustic coupling. LV is a candidate measurement technique for embedded sensing in advanced combustors. Based on a test case involving a reference pulsator, we described in this paper the jet dynamics generated by the siren of a prototype injector with help of PIV in isothermal free jet, as well as an enclosed pulsed flame at intermediate pressure with the help of LV. A fully automated measurement technique was developed and detailed, allowing rapid flow dynamic description, with related post-processing routines for phase defined data. For practical purpose, LV can map the density fluctuations with help of a reference signal. The similarity in the observed jet dynamics between PIV and LV was underlined. The volume of LV data is relatively small in comparison with more demanding methods such as PIV to describe a given coherent structure dynamic. The advantage of LV is its high spectral sensitivity, and ability to detect fluctuations in the high-frequency domain, where other detection techniques offer a lower signal-to noise ratio. We established in this paper that LV allows measurement in an enclosed jet configuration in presence of optical accesses and at intermediate pressure.

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