Using Dual Laser Vibrometry to monitor the stability of gas turbine combustion

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Abstract

Laser vibrometry (LV) is originally a laser-based measurement technique dedicated to the analysis of surface vibrations. This technique was adapted at TU Graz as a line-of-sight measurement technique for the observation of coherent vortices in a turbulent flow, and then lately as a technique for monitoring the stability of an air-methane flame using two instruments (Dual Laser Vibrometry - DLV). This paper reports on measurements realised on a resonant flame (premixed air-methane, quarter-wave resonator, amplification with a siren). A remarkable relation between the flame dynamics, and phase-defined DLV measurements can be observed. Signal processing will be shortly described. In order to support the observations, and correlate the results with data from other measurement techniques, high-speed schlieren visualisations and stereoscopic Particle-Image-Velocimetry (PIV) were used. The paper eventually addresses issues regarding quantification (from line-of-sight to local measurement, amplitude analysis of the density fluctuations ρ' and comparison with the local thermoacoustic couplings). One recommended application of DLV is its ability to perform precise and low-cost combustor benchmark stability tests (time-resolved measurement, broad frequency spectrum, no need for seeding, very high sensitivity, measurement possible over the whole combustion volume).

Introduction

The issue of the present work is the development of measurement techniques for detailed analysis of turbulent combustion, more specifically the analysis of coherent structures involving thermoacoustic couplings. The well-known industrial problem that lies behind is the bridle of performance for power and propulsion gas turbines due to the presence of combustion instabilities. These are detrimental - if not critical - for the system operability and integrity. The common research effort focuses on the development of control strategies and design guidelines towards a steady-at-once combustor, with extended working range in the lean combustion region for environmental issues.

Our motivation is to analyse local and temporal density fluctuations ρ' of the fresh mixture as well as of the burnt gases. This quantity is related to both pressure fluctuations p' and heat release fluctuations q'. As far as the Rayleigh criterion is concerned [1], a strong amplification of ρ' is also a potential marker for instability detection. In our experiment, a premixed methane-air burner is placed at the end of a quarter-wave resonator, so that the flame resonant modes are known. A siren can amplify these modes and enhance the jet dynamics. As a result, an instability of the type vortex-driven combustion (Yu et al. [2]) is reproduced.

The real-time analysis of ρ' is performed with help of a set of two laser vibrometers (Dual LV, see Giuliani et al. [3]). This is a new application of this instrument, usually dedicated to surface vibration analysis [4], that was also proved to detect coherent turbulence in a turbine flow [5,6]. Here, DLV is used to analyse the flame-vortex interaction in time and space. Observations are compared with high-speed schlieren visualisations, as well as with stereoscopic PIV measurements. We demonstrate that DLV provides valuable information on the flow dynamics outside and inside the flame, and offers the advantage of an easy set-up and simple use. The measurement is highly sensitive and non-intrusive. A line-of-sight measurement penetrates the flame core, which partly avoids side-effect disturbance (e.g. cooling jet noise perturbing fast pressure probe measurements on an industrial burner). This paper also discusses quantification issues of ρ', and eventually state-of-the-art DLV is recommended as a burner test bench method for stability qualification.

Experimental set-up and operating conditions

The atmospheric single-burner sector that was fully engineered at TU Graz [3] allows the analysis of a premixed air-methane flame under controlled inlet pulsed flow conditions. All parameters of importance are reported in table 1.

Resonator and siren

The important components of the test rig are a siren provided by the ONERA [9,10] and used as a flow exciter (figure 1), a long pipe used as a resonator and the burner itself (figure 2, up). The supply pipe induces a quarter-wave resonance (closed-open resonator with a nozzle upstream and of an opened-end downstream) as well as higher-order harmonic fluctuations. The 3m length enhances the fundamental mode 25Hz and all of its odd multiples (75Hz, 125H, 175Hz...). The siren amplifies these significant resonant modes to achieve pressure fluctuations comparable with a real thermoacoustic coupling.

Premixed air-methane burner

Premixing takes place in the supply pipe. The injection module combines a Venturi nozzle with an axial swirler to accelerate the flow, keep the flame away from the front plate and prevent flash-back (figure 2, down). The flame is swirl-stabilised due to the swirler. We chose axial instead of radial swirler blades so that the injector remains as acoustically transparent as possible, at the cost of a relatively low swirl number.

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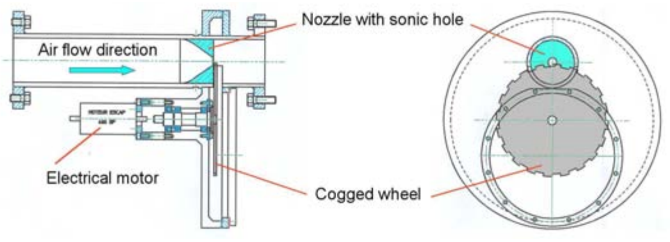

Fig. 1. ONERA siren, where a sonic jet sheared by a cogged wheel rotating at controlled velocity sets an air flow modulation at the desired frequency [9].

CONFIGURATION	
Resonator length	3m
Amplified modes	25 + N*50 Hz, N={1, 2, 3...}
Axial swirl angle	45º
Number of blades	3
Venturi ratio	2/5
Chamber dimensions	100*100*120mm

OPERATING CONDITIONS	
P and T_{inlet}	room conditions, 1 bar, 300K
Air feed	10 g/s
Methane feed	0.47 g/s
Equivalence ratio	Φ=0.8
Axial inlet velocity	U_{mean}=12.6m/s
Injector pressure loss	ΔP_{inj} = 240 Pa
Swirl number [7]	0.8
Max. T_{wall}	950 K (uncooled)
Siren excitation range	110-120 dB SPL [8]
T_{out}	1300 K

Table 1
Configuration and operating conditions

Operating conditions

The operating conditions are reported in table 1. In this article we focus mainly on the free-jet configuration. The flame pattern in the near injection zone is visible in figure 3. In free-jet mode, the flame attaches to the tip of the injector (zone labelled I), where surrounding ambient air is aspired and entrained. After that, the fresh injected mixture ignites and the flame expands along a cone-shaped flow surrounding the central recirculation zone generated by the swirler (zone labelled II, the cone mean solid angle is 30 degrees). The zone labelled III marks the internal recirculation breakdown zone, where the highly turbulent flame ends.

Measurement techniques

In order to demonstrate the ability of DLV to perform a refined analysis of the flame dynamics, supporting techniques such as fast schlieren visualisation and phase-averaged PIV were applied.

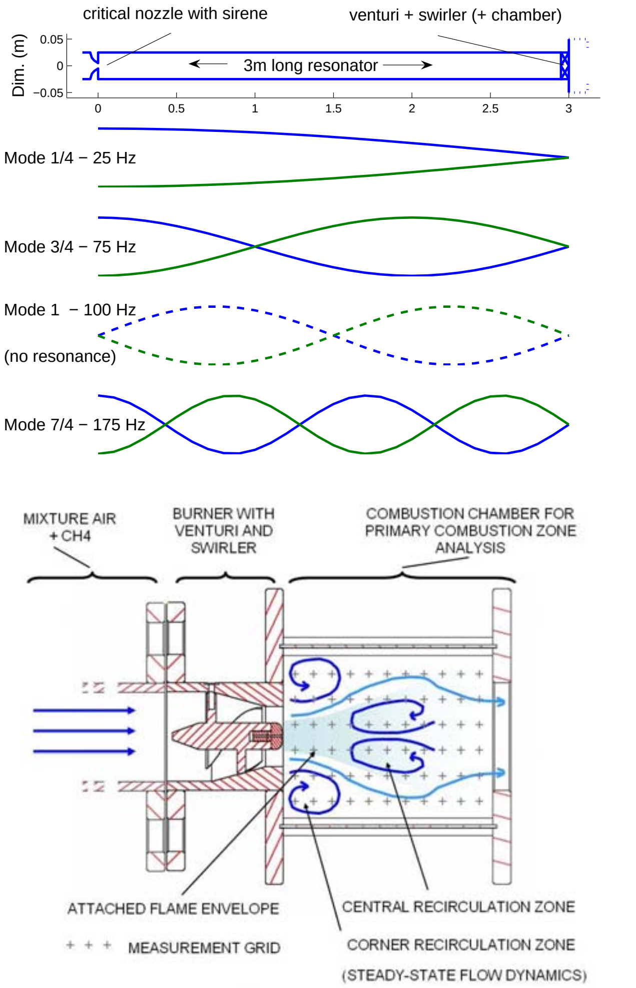

Fig. 2. Test rig. Up: amplified modes with the siren and quarter-wave resonator. Down: premixed air-methane burner detail with optional bluff-body combustion chamber.

DLV - Dual Laser Vibrometry

The principle of LV is shown in figure 4. A laser interference pattern between a reference beam and an object beam (reflecting on the studied surface) is analysed. If the surface moves, the path difference between the two beams changes and so the interference. In order to detect motion amplitudes greater than the laser wavelength, and to distinguish a forward from a rearward movement, a Bragg cell is used to slightly shift the reference beam wavelength (similar trick as the one used for LDV). Steady-state is then represented by a fixed frequency corresponding to the modulated interference. Any surface motion will provoke a Doppler effect (compressive or expansive) on this carrierwave. A frequency demodulation allows to derive the vibration frequency and the motion amplitude of the object surface.

Mayrhofer and Woisetschläger [5] used a variant of this technique for density fluctuation analysis of ambiant air, keeping the geometrical path constant (the object surface is a mirror at rest) so that mainly density fluctuations alter the optical path, advancing (negative density gradient) or retreating (positive gradient) the phase front of light. As a result, LV can detect

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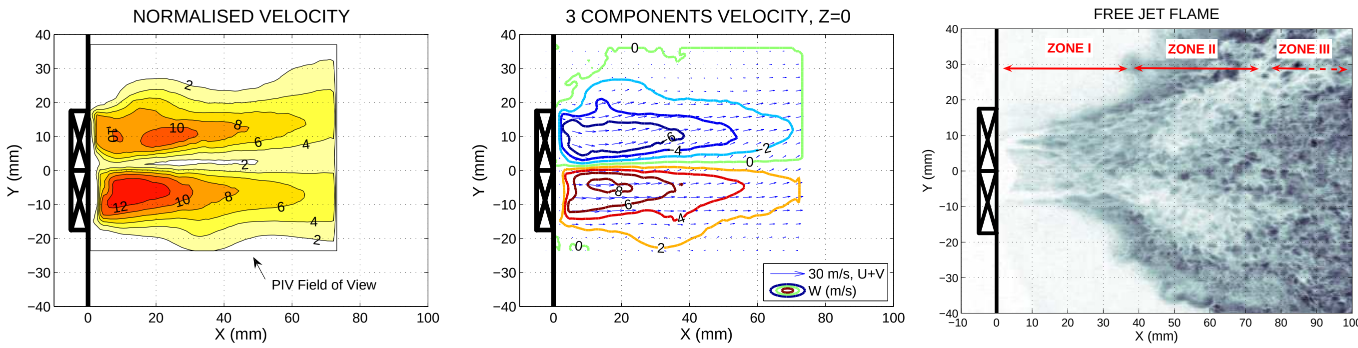

Fig. 3. Flame aspect in free jet mode. Left and middle: velocity flowfield of the injection (3-components PIV measurements at isothermal conditions). Right: schlieren image of the flame, and flame zone subdivision (compare figure 5).

the presence of passing-by coherent structures. The relationship between LV signal voltage u and density fluctuation ρ' is derived from [5,6] as follows:

$$u_f = \frac{G}{k} \int_Z \frac{\partial \rho'_f}{\partial t} dz \tag{1}$$

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, so that u_f and ρ'_f correspond to the narrowly band-passed signals of the time-signals $u(t)$ and $\rho'(t)$ at frequency f.

LV has the advantage of a higher sensitivity in comparison with other line-of-sight laser-based measurement techniques [11], plus the fact that the object beam laser passes twice through the measurement volume. We used two Polytech OVD 353 which are compact systems, user-friendly and fast to set-up. DLV requires one instrument as a fixed-point reference measurement, while the second one scans the measurement surface of interest (see figure 4 for DLV arrangement and figure 2, down for the specific measurement grid).

Schlieren and rapid camera

Schlieren imaging technique is commonly used for density gradient measurements, and vortex-driven combustion instabilities are often analysed by means of schlieren visualisation (e.g. [12]). A high-speed camera model Kodak MCA-SR was used, at a sampling rate of 1kHz with 0.5ms exposure time, short enough to freeze the flame patterns.

Samplings over one period of these visualisations are displayed in figure 7a.

PIV - Stereoscopic Particle Image Velocimetry

Particle-Image Velocimetry [13] measures the velocity flowfield in a plane illuminated by two consecutive laser flashes. Stereo PIV reconstitutes the 3D velocity components in the planar field of view. The PIV system consists of a Nd:YAG-Laser (532nm - green light, 120mJ/pulse, pulse duration 3-5ns, 15Hz) from New Wave GEMINI. The two cameras used are DANTEC 80C60 HiSense models (1280x1024 pixels, 12bit greyscale), driven by a PIV Processor model DANTEC FLOWMap 1500. We processed the images with the DANTEC PIV-software FlowManager v4.60.28.

An Aerosol generated the DEHS tracer particles (Di-Ethyl-Hexyl-Sebacat, specific particle size 0.7-1μm) seeding the flow. We used it for isothermal jet characterisation (figure 3) and also for combustion analysis. Here the fact that the particles burn and therefore quickly disappear facilitates the recognition of the flame boundaries and surrounding coherent structures (figure 7b).

Special processing techniques

The phase-averaging technique used for time-triggered measurements such as PIV are described in [10]. The data processing used for DLV is described in [3]. The synchronisation signal is either the siren signal, or the fixed LV signal.

For the vortex analysis performed with PIV (figure 7c), the Λ_2 criterion from Jeong & Hussain [14] was used to sort the multiple shear layers out from the vorticity field.

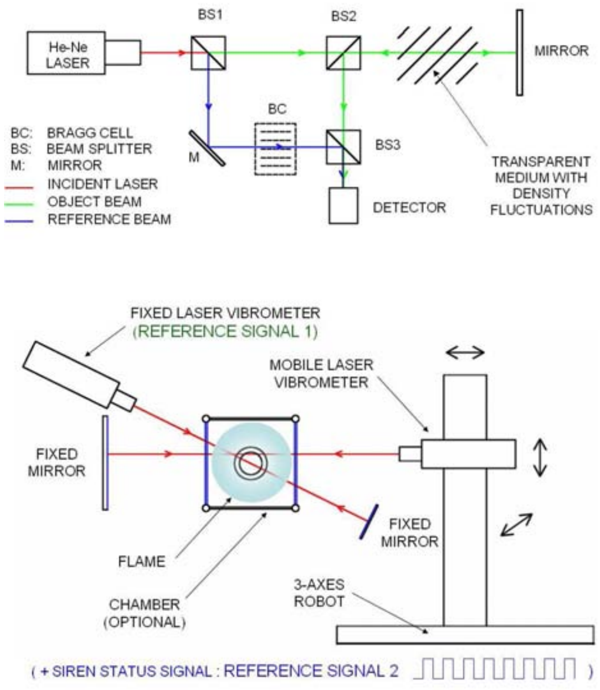

Fig. 4. Principle of laser vibrometry and DLV arrangement

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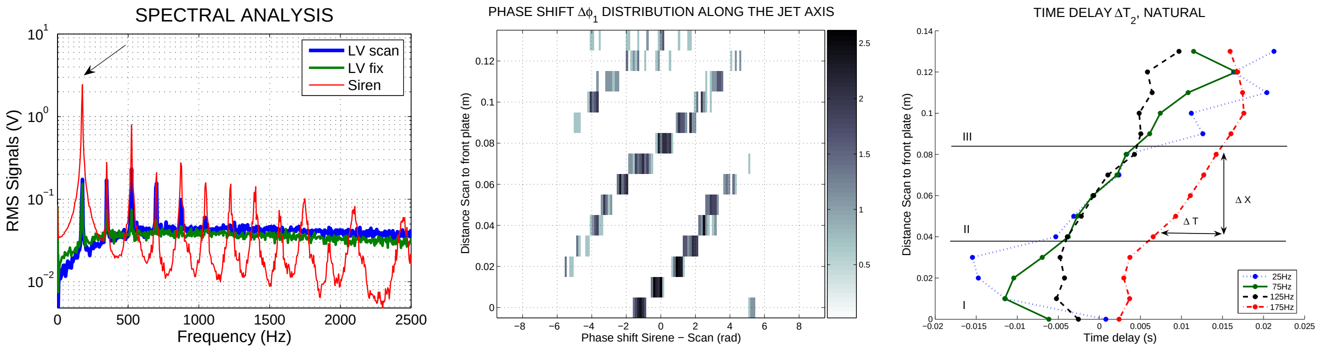

Fig. 5. Signal processing. Left: identification of the resonant mode and measurement of the phase shift between scanning LV and fixed one. Middle: coherence PDF, as a function of distance X. Right: determination of the advection velocity of the observed wave for the natural resonant modes (no siren). Note the corresponding flame zones from figure 3

The three essential steps of DLV processing are represented in figure 5 (see [3] for technical details). A spectral analysis performed on the time signal $u(t)$ shows a dominant resonant mode (175Hz, left). The phase-shift $\Delta\phi$ at frequency peak f between the scanning LV and the fixed one is measured N times. After that the coherence level between the two signals at a fixed point is reconstructed in the time-domain over a full pulsation period τ. The resulting coherence Probability Density Function (PDF) is traced as a function of the distance between the scanning LV and the injector (middle figure). Here we identify clearly a convective effect along the jet axis. The derivation of the advection velocity is based on the measurement of the PDF slope (figure 5 left).

The corresponding output voltage fluctuation $u_f(t)$ is then computed as the product of the coherence PDF times the scanning LV frequency peak intensity, and mapped (figure 6, left). The relative density fluctuation ρ'_f is numerically adapted from equation 1 as:

$$\rho'_{f\ LS}(t + d\tau) \simeq \rho'_{LS}(t) + \frac{k}{GZ} u_f(t + d\tau) d\tau \qquad (2)$$

with end condition $\bar{\rho}'_{f\ LS} = 0$, where LS means integrated over the line-of-sight depth Z. We suppose the factor term k/GZ constant (the variation of G is neglected [15]). The resulting map is represented in figure 6, middle. Finally, due to the nearly axial symmetrical geometry of the jet, an Abel transform is possible in order to retrieve the local density fluctuation ρ'. Although the Abel inversion generates its major uncertainty on the centerline (this underlines the lack of axial symmetry of the jet), it also positions the observed structures more precisely at the jet periphery than the integral measurement does 6, right.

Results

The shape modulation of a flame governed by a vortex-driven-instability is reproduced with help of the ensemble siren+resonator pipe. The flame is attached forming a tube at the tip of the injector (figure 7a). After that, a mushroom-shaped circumferential instability appears around this tube, with the development of a Kelvin-Helmholtz instability matching in position the outer ring vortices, at the boundary of which the flame front evolves. This structure is advected with the flow in the meantime as the flame roll-up closes, and so on. The siren excitation frequency drives the mixing layer instability.

The PIV seeding pictures from figure 7b correspond to the maximum intensity per pixel integrated over the whole 200 images necessary for a measurement. The central bright zone in the middle corresponds to the flame (no velocity measurements are valid there, while too little tracer made it through the flame). The shape of this flame envelope allows the synchronisation by pattern recognition with high-speed schlieren images.

Another interpretation of the PIV data lies in the superimposed velocity and vorticity measurements (Fig.7c) in the jet periphery. The velocity vectors placed along the flame expansion cone indicate a redundant bottleneck shape [9], at the shoulder of which a pair of clockwise (red colour on the vorticity maps, unit is 2πrad/s) and anticlockwise (blue) ring vortices are evolving - one down the flow inside the jet envelope and one up the flow outside of the jet. These vortices are generated at the front plate by the mass flow modulation, detach from the front plate and then are transported by the flow. The advection velocity of these structures is usually about half of the injection velocity [16]. Note also that on our configuration, these vortices work as quadrupole placed around the major flame instability.

Applying the process of figure 6, one derives essentially with DLV the dynamics of deformation of the flame front (Fig.7d). The description of the mushroom-like roll-up motion is remarkable, and observable within the depth of the flame where both schlieren and droplet-seeding-PIV are blind. ρ' is as expected essentially driven by the temporal flame front position.

Discussion

DLV allows the fast recognition of resonant modes in a turbulent flame (the calculation of signal coherence suffices for the identification and measurement of structure advection velocity, as previously shown in figure 5), as well as it determines the relative density fluctuation in line-of-sight (Abel transform allowed if the jet geometry permits it). This method is lightweight in terms of instrumentation and data volume, and relatively low-cost as well. It is non-intrusive, requires no seeding and is extremely sensitive. The line-of-sight measurement provides

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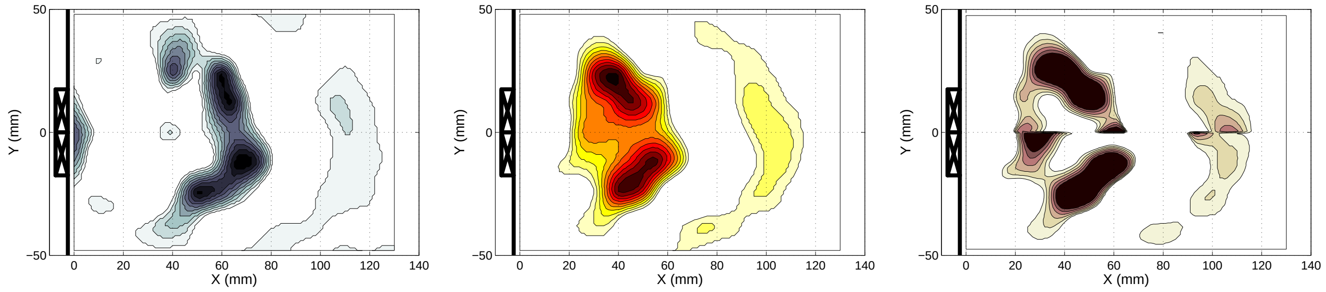

Fig. 6. DLV mapping process. Left: Map of the scanning LV filtered voltage $u_f(d\tau)$ at frequency $f = 175Hz$ and phase subperiod dτ. Middle: map of the relative density fluctuation $\rho'_{f\ LS}(d\tau)$ (line-of-sight, computed with equation 2). Right: Abel transform of the latter to obtain a radial distribution of density fluctuation within the plane.

information on the very core of the flame, and not just a side information as any surface sensor would do. Therefore a single LV could be more efficient than for example a microphone to deliver a proper reference signal for time-triggered instruments. DLV provides information with a satisfactory signal-to-noise ratio from naturally resonant flame, according to tests performed without activating the siren (figure 5, right).

Current developments at TU Graz focus on the validation of this method on a similar combustor at intermediate pressure levels. In the near future, an industrial natural gas burner as well as a LPP module (premixed air-kerosene mixture) shall be tested with DLV. From the fundamental research point of view, realtime determination of the local Rayleigh criterion is also an important issue.

Conclusion

A validation experiment for a new turbulent combustion diagnostic technique was performed on a resonant air-methane premixed flame in order to establish the capacity of DLV to identify the main modes of resonant flame dynamics, and to analyse in time and space the density fluctuations ρ'. The potential and relative simplicity of this technique for flame coherent turbulence analysis are emphasised. State-of-the-art DLV is recommended as a test bench method at ambient conditions for stability qualification of natural gas burners.

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References

[1] A. Putnam, W. Dennis, A study of burner oscillations of the organ-pipe type, Trans. ASME 75 (15).

[2] K. H. Yu, A. Trouve, J. W. Daily, Low-frequency pressure oscillations in a model ramjet combustor, J. of Fluid Mechanics 232 (1991) 47–72.

[3] F. Giuliani, B. Wagner, J. Woisetschläger, F. Heitmeir, Laser vibrometry for real-time combustion stability diagnostic, in: Proc. of the ASME Turbo Expo 2006, Barcelona, Spain, 2006, GT2006-90413.

[4] A. Levin, New compact laser vibrometer for industrial and medical applications, in: Third int. conf. on vibration measurements by laser techniques, Vol. SPIE Proc Series 3411, 1999, pp. 61–67.

[5] N. Mayrhofer, J. Woisetschläger, Frequency analysis of turbulent compressible flows by LV, Experiments in Fluids 31 (2001) 153–161.

[6] B. Hampel, J. Woisetschläger, Frequency and space resolved measurement of local density fluctuations in air by laser vibrometry, Measurement Science & Technology (2006) 2835–2843.

[7] J. Beér, N. Chigier, Combustion Aerodynamics, Applied Science publishers Ltd, 1972, pp. 100–146.

[8] F. Giuliani, A. Schricker, A. Lang, T. Leitgeb, F. Heitmeir, High-temperature resistant pressure transducer for monitoring of gas turbine combustion stability, in: Proc. of the 18th ISABE conference, Beijing, China, 2007, accepted.

[9] F. Giuliani, P. Gajan, O. Diers, M. Ledoux, Influence of pulsed entries on a spray generated by an air-blast injection device - an experimental analysis on combustion instability processes in aeroengines, Proceedings of the Combustion Institute 29 (2003) 91–98.

[10] F. Giuliani, O. Diers, P. Gajan, M. Ledoux, Characterization of an air-blast injection device with forced periodic entries, in: Proceedings of the IUTAM Symposium on Turbulent Mixing and Combustion, Pollard and Candel (eds) Kluwer Academic Publ., 2002, pp. 327–336.

[11] F. Giuliani, C. Hassa, Analysis of air-blasted kerosene vapour concentration at realistic gas turbine conditions using laser infra-red absorption, in: Proc. of the 3rd ECM, European Combustion Meeting, Chania, Greece, 2007.

[12] K. McManus, T. Poinsot, S. Candel, A review of active control of combustion instabilities, Prog. Energy Combust. Sci. 19 (1993) 1–29.

[13] T. Arts, H. Boerrigter, M. Carbornaro, J. Charbonnier, G. Degrez, D. Olivari, M. Riethmuller, R. van den Braembussche, Measurement techniques in fluid dynamics - an introduction, VKI LS 1994-01.

[14] J. Jeong, F. Hussain, On the identification of a vortex, Journal of Fluid Mechanics 285 (1995) 69–94.

[15] W. J. Gardiner, Y. Hidaka, T. Tanzawa, Refractivity of combustion gases, Combustion and Flame 40 (1980) 213–219.

[16] J. Panda, K. McLaughlin, Experiments on the instabilities in a free swirling jet, in: 28th Aerospace Sciences Meeting, 1990, AIAA 1990-0506.

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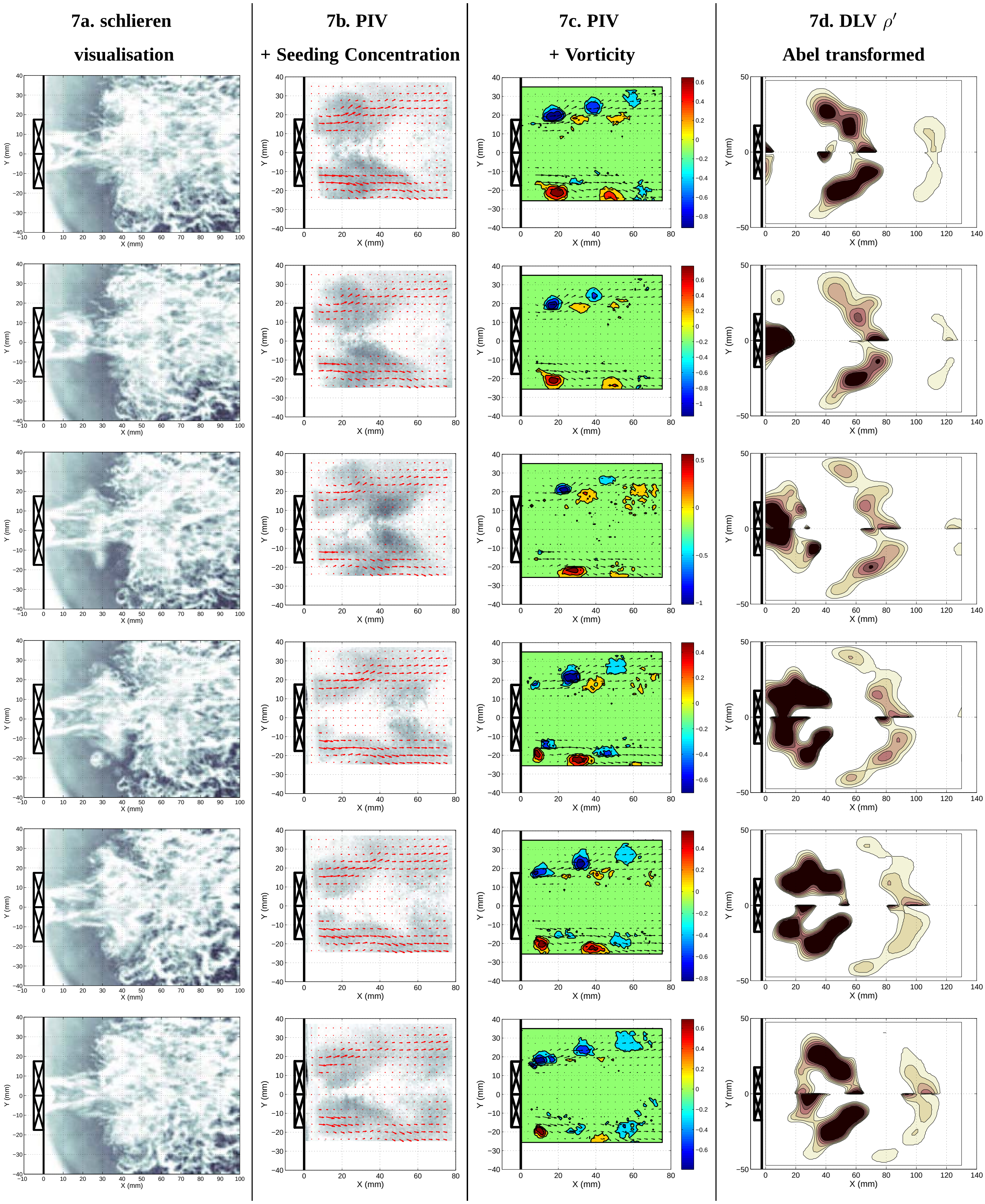

Fig. 7. Advected structures observed with PIV and schlieren technique. Pulsation 175 Hz. Six phase-locked subperiodes from 0ms to $5\tau/6$=4.75ms are displayed with incremental time step $\tau/6$=0.95ms from top to bottom.