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Non-invasive seedingless measurements of the flame transfer function using high-speed camera-based laser vibrometry

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ABSTRACT

The characterization of modern jet engines or stationary gas turbines running with lean combustion by means of swirl-stabilized flames necessitates seedingless optical field measurements of the flame transfer function, i.e. the ratio of the fluctuating heat release rate inside the flame volume, the instationary flow velocity at the combustor outlet and the time average of both quantities. For this reason, a high-speed camera-based laser interferometric vibrometer is proposed for spatio-temporally resolved measurements of the flame transfer function inside a swirl-stabilized technically premixed flame. Each pixel provides line-of-sight measurements of the heat release rate due to the linear coupling to fluctuations of the refractive index along the laser beam, which are based on density fluctuations inside the flame volume. Additionally, field measurements of the instationary flow velocity are possible due to correlation of simultaneously measured pixel signals and the known distance between the measurement positions. Thus, the new system enables the spatially resolved detection of the flame transfer function and instationary flow behavior with a single measurement for the first time. The presented setup offers single pixel resolution with measurement rates up to 40 kHz at an maximum image resolution of 256 px × 128 px. Based on a comparison with reference measurements using a standard pointwise laser interferometric vibrometer, the new system is validated and a discussion of the measurement uncertainty is presented. Finally, the measurement of refractive index fluctuations inside a flame volume is demonstrated.

Keywords: interferometry, high-speed camera, single pixel resolution, thermo-acoustics

1. INTRODUCTION

Environmental protection and low fuel consumption are priorities of the industrial development of modern jet engines or stationary gas turbines due to new emission-restrictions.¹ Therefore, lean combustion, i.e. a low fuel-air-ratio inside the flame, became an often used technique for combustion engines since it provides reduced pollutant emissions and increased efficiency, respectively. A common example for such combustions are swirl-stabilized flames. However, such systems exhibit flame oscillations based on the thermo-acoustic coupling between fluctuations of the heat release rate and the pressure.² These oscillations lead to flame instabilities, influencing the combustion properties, or even the extinction of the flame, in the worst case. Hence, the characterization of the flame during the industrial development process of such combustion engines is crucial. To this aim, the flame transfer function (FTF) is measured, which is the frequency dependent ratio

$$\text{FTF}(f) = \frac{\dot{Q}'(f)/\bar{\dot{Q}}}{v'(f)/\bar{v}} \quad (1)$$

between the line-of-sight and time average of the heat release rate $\bar{\dot{Q}}$ inside the flame, the line-of-sight and time average flow velocity $\bar{v}$ at the combustor outlet and the amplitude of their temporal fluctuations at the frequency f of both quantities denoted by $'$, respectively.³ Accordingly, the investigation of the flame characteristic

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necessitates temporally resolved measurements of the heat release rate and the flow velocity inside the flame volume.

Previous measurements of the FTF were achieved using acoustical excitation of the flame and an array of multiple microphones, yet, this technique provides only information of the global flame characteristic.⁴ Investigation of the heat release rate inside the flame volume can be realized by chemiluminescence of hydroxides, but only under the condition of adiabatic flames,⁵ which is not fulfilled at technically premixed flames. Spatially resolved measurements of the flow velocity can be realized using well known techniques such as particle image velocimetry or Doppler global velocimetry,⁶ but both techniques require the usage of tracer particles, which influences the thermodynamic behavior of the flow. Thus, such measurement techniques will not be considered further.

Simultaneous seedingless measurements of both the heat release rate and flow velocity were achieved using multiple laser interferometric vibrometers (LIV) and signal correlation.^{7,8} In doing so, the measurement of fluctuations of the heat release rate is possible due to its linear relation to the refractive index inside flames. The measurement of the flow velocity is possible by evaluation of the phase delay between two vibrometer signals and the known distance between the measurement positions.⁹ However, only single line-of-sight measurements, but no simultaneous field measurements have been done and, thus, the detection of complex spatio-temporal flow behavior is not possible.

In order to overcome these limitations, a high-speed camera-based laser interferometric vibrometer (CLIV) is designed for non-invasive seedingless measurements of the FTF inside swirl-stabilized technically premixed flames. The CLIV offers single pixel resolution with measurement rates up to 40 kHz at an maximum image resolution of 256 x 128 px. Based on a comparison with reference measurements using a standard pointwise laser interferometric vibrometer, the new system is validated and a discussion of the measurement uncertainty is presented. Finally, the measurement of refractive index fluctuations inside a flame volume is demonstrated.

2. MEASUREMENT PRINCIPLE AND SETUP

An LIV in general is an interferometric measurement system, typically based on a Mach-Zehnder-setup, as depicted in Fig. 1. The laser beam is separated into a measurement path (1) and a reference path (2). Using the high-speed camera-based laser interferometric vibrometer (CLIV), the superposition of both beams is detected with single pixel resolution, resulting in a modulated intensity signal

$$I \sim [1 + V \cos(\Delta\varphi)] \quad (0 \leq V \leq 1) \quad (2)$$

at every pixel with the interference contrast V and the phase shift

$$\Delta\varphi(z, t) = 2\pi f_B t + \frac{2\pi}{\lambda} 2L(z, t) \quad (3)$$

with the carrier frequency f_B , the laser wavelength λ and the length of the optical path $L(z, t)$, which depends on time t and the geometric path z between the LIV and the reflector. Further, the instantaneous frequency of the intensity signal results to

$$f_I(z, t) = \frac{\partial \Delta\varphi}{2\pi \partial t} = f_B + \frac{2}{\lambda} \dot{L}(z, t) = f_B - f_D(z, t) \quad (4)$$

with the Doppler frequency f_D . Under the condition of a constant length of the geometric path z , the length of the optical path results to

$$L(z, t) = \int_z n(l, t) dl \quad (5)$$

with the refractive index n , which is linear depending on the fluids density ρ , according to the Gladstone-Dale relation

$$G = \frac{n - 1}{\rho} \quad (6)$$

with the material dependent Gladstone-Dale constant G . Therefore, it is possible to detect the temporal density fluctuation $\dot{\rho}$ integral along the path z from the measured intensity signal, according to eq. (2). The density fluctuation depends on the pressure variation $\dot{p}$ and the local fluctuation of the heat release rate $\dot{q}$ within an infinitesimal volume according to

$$\dot{\rho} = \frac{1}{c^2} \dot{p} - \frac{\kappa - 1}{c^2} \dot{q} \quad (7)$$

with the sound velocity c and the temperature dependent adiabatic exponent κ .¹⁰ Since within flames the density fluctuation is dominated by the heat release rate, the contributions based on pressure variations are negligible and eq. (4) - (7) merge into the linear relation

$$f_D(z, t) = \frac{2G(1 - \kappa)}{\lambda c^2} \int_z \dot{q}(l, t) dl = \frac{2G(1 - \kappa)}{\lambda c^2} \dot{Q}(z, t). \quad (8)$$

Thus, the CLIV provides spatio-temporally resolved measurements of the integral heat release rate $\dot{Q}$ along the path z , crossing the flame volume in its entirety. Note, that the CLIV is furthermore capable of seedingless sound field measurements in areas where the density variation is dominated by the fluctuation of the pressure, as shown in eq. (7)-(8).

Figure 1. Schematic setup of the high-speed camera-based laser interferometric vibrometer (CLIV): the laser beam ($\lambda = 532 \text{ nm}$) is split into measurement path (1) and reference path (2). In the latter, the laser beam is directed through two acousto-optical modulators (AOM) running at the center frequency $F = 200 \text{ MHz}$ and $F + f_B$, respectively. Based on the incidence angle Θ_B and the frequency difference between AOM 1 and AOM 2, the laser light frequency f_0 is shifted by the carrier frequency $f_B \approx 60 \text{ kHz}$. In the measurement path the laser light frequency is Doppler-shifted by the frequency f_D based on the fluctuation of the heat release rate inside the flame along the path z . The superposition of both beams on the camera sensor results in an oscillating intensity signal with the frequency $(f_B - f_D)$.

The maximum measurable fluctuation frequency is limited by the camera frame rate f_C , since the fluctuating intensity signal in eq. (2) has to be sampled according to the Nyquist-Shannon sampling theorem, which necessitates the condition

$$f_C > 2(f_B + |f_D|). \quad (9)$$

Additionally, the condition $f_B > |f_D|$ has to be fulfilled in order to avoid ambiguousness at the frequency evaluation.¹¹

The experimental setup comprises a laser Samba 532 nm from the manufacturer *Cobolt*, which provides a coherence length of 300 m and a maximum output power of 500 mW. Using a single mode fiber and a collimation optic providing a beam diameter of 2 mm, the laser beam is coupled to the vibrometer setup. After splitting the

incident laser light, the measurement beam is magnified by a variable set of optics in order to achieve a field of view up to $50\text{ mm} \times 50\text{ mm}$ in the measurement volume. At the end of the measurement volume, the beam is reflected using a retro-reflector from the manufacturer *3M*, which suppresses beam distortions for example due to variations of the refractive index inside a flame volume. The reflector consists of microscopic glass spheres allowing an parallel shift of the reflected beam smaller than $100\text{ }\mu\text{m}$. In the reference path, the laser frequency shift is realized by a cascade of two acousto-optical modulators (AOM) MT200-VIS from the manufacturer *AA Opto-Electronic*, running at the center frequency $F = 200\text{ MHz}$ and $F + f_B$, respectively. Based on the incidence angle Θ_B and the frequency difference between AOM 1 and AOM 2, the laser light frequency f_0 is shifted by the carrier frequency $f_B \approx 60\text{ kHz}$. This carrier was chosen in order to provide a sufficient measurement range for the expected bandwidth of the Doppler frequency spectrum of $\pm 30\text{ kHz}$, which is known from former investigations at similar swirl-stabilized flames.¹² Accordingly, a camera frame rate $f_C = 200\text{ kHz}$ was chosen in order to fulfill the precondition in eq. (9), which limits the measurement range for the Doppler frequency to $\pm 40\text{ kHz}$. The high frame rate was achieved using a high-speed camera Phantom v1610 from the manufacturer *Vision Research*, which was used in previous measurement systems.^{13,14} The camera provides a pixel pitch of $28\text{ }\mu\text{m}$ and a maximum frame rate of 1 MHz at a reduced resolution of $128\text{ px} \times 16\text{ px}$. At the chosen frame rate, the resolution is limited to a maximum of $256\text{ px} \times 128\text{ px}$. After detecting the modulated intensity signal, the temporal resolved Doppler frequency is achieved using a quadrature demodulation technique for each pixel.

3. SYSTEM CHARACTERIZATION AND MEASUREMENT UNCERTAINTY

For the purpose of validation and for characterization of the measurement uncertainty of the new system, test measurements using the CLIV and a standard LIV from the manufacturer *Polytec* are performed. First, a comparison of the noise levels of both systems is performed. Additionally, the mechanical vibration of a loudspeaker's wooden housing is investigated as test case using both measurement systems simultaneously.

3.1 Comparison of system noise

In order to characterize the CLIVs system noise, a measurement under standard room conditions and no measurement object within the measurement beam is performed with LIV and CLIV simultaneously. For both systems the measurement duration is 60 s . Since field measurements are required, no pixel binning, but a single pixel evaluation of a center pixel as an example is performed using the CLIV and compared with the point-wise measurement using the LIV as reference. As a comparison of the results, the power spectral density (PSD) of the measured Doppler frequency is depicted in Fig. 2(a) with a frequency resolution of 1 Hz . Although no measurement object is placed in the measurement beam, several narrow-banded fluctuations mainly in the lower frequency range up to 1 kHz were detected, e.g. due to noise from the air conditioning and computer fans or mechanical vibrations caused by work in neighboring laboratories. Based on the distribution of these background noises in the laboratory or the location of disturbing vibrations, the two measurement systems detect different amplitudes of these disturbing signals, since it is not possible to place both systems in the same position.

Additionally to the narrow-banded disturbing signals, the characteristic broadband detector noise of both measurement systems can be seen in Fig. 2(a). The standard LIV provides a nearly constant noise level of $2\text{ Hz}^2/\text{Hz}$ over the whole frequency range of 40 kHz . On the contrary, the single pixel noise level of the CLIV stays constant at $1\text{ Hz}^2/\text{Hz}$ up to a frequency of 1 kHz and then increases up to $20\text{ Hz}^2/\text{Hz}$ at the end of the measurable frequency range. As a result, both systems provide similar noise levels in the frequency range up to 1 kHz . Furthermore, the new CLIV provides, compared to the conventional LIV system, the same relative uncertainty

$$u_{\text{rel}} = \frac{u_{f_D}(f)}{\overline{f_D}(f)} = 15\%, \quad (10)$$

averaged over the whole spectrum, where $\overline{f_D}(f)$ is the mean value of the measured amplitude of the Doppler frequency at the oscillation frequency f averaged over 60 samples and $u_{f_D}(f)$ its standard uncertainty, respectively. For a field of view of $50\text{ px} \times 50\text{ px}$, u_{rel} is nearly constant among the pixels with a maximum variation of $\pm 1\%$. Hence, the CLIV provides the same relative uncertainty and a similar system noise like the standard LIV.

3.2 Measurement of mechanical vibration

As stated before, the CLIV system is proposed for measurements of refractive index fluctuations. Since these fluctuations result mostly in a low signal-to-noise ratio (SNR) and an unknown quantitative behavior, their usability as reference objects is limited. For this reason, the mechanical vibration of a loudspeaker's wooden housing is taken as experiment for comparing measurements using LIV and CLIV simultaneously, in order to validate the new system quantitatively. A sine wave with frequency $f_{sound} = 440$ Hz is being fed to the loudspeaker. As before, the CLIV is evaluated at a center pixel over a measurement time of 60 s. The PSD of the measured Doppler frequency is shown for both systems in Fig. 2(b). As a result, both measurement systems detect a maximum PSD of 3×10^7 Hz²/Hz for the dominant vibration at f_{sound} . Additionally, higher harmonics are detected by each system, respectively. Accordingly, the vibration is successfully measured using the CLIV and, thus, the new system is validated by means of the comparison with the results of the standard LIV.

Figure 2. Estimation of the power spectral density (PSD) of the Doppler frequency based on a measurement duration of 60 s, measured with LIV and CLIV simultaneously. (a) Measurement under standard room conditions without a measurement object in the measurement beam. (b) Measurement of a loudspeaker's vibrating wooden housing.

4. SYSTEM APPLICATION

First measurements of refractive index fluctuations inside a flame volume using the CLIV are performed at a premixed swirl-stabilized flame, which was used in previous investigations regarding the measurement of the flow velocity.⁶ The flame exhibits characteristic oscillations of the heat release rate and velocity up to several kHz, which are detectable in the emitted sound field outside the flame volume, as well. Therefore, a qualitative comparison between microphone measurements and measurements using a single camera pixel is depicted in Fig. 3. The microphone is placed in a distance of 0.5 m to the center of the flame. The measurement beam of the CLIV is oriented through the center of flame volume with a constant height of 12 mm over the combustor outlet. The shown results are averaged over 60 acquisitions with a duration of 1 s, resulting in a frequency resolution of 1 Hz.

Both systems detect dominant oscillations at 700 Hz and 710 Hz as well as several minor oscillations in the shown frequency range. This observed spectrum is in good agreement with previous measurements.⁶ As shown in Fig. 3(b), the narrow-banded fluctuations of the refractive index are clearly detectable with amplitudes up to six order of magnitude higher than the system noise shown in Fig. 2. Additionally, the measured broadband energy contribution from the turbulent flow inside the flame volume is three orders of magnitude higher than the CLIVs system noise. Thus, the new systems usability for measurements inside technically premixed swirl-stabilized flames is demonstrated.

Figure 3. Flame measurements: (a) Measurement of the sound field emitted by the flame using a microphone. (b) Measurement of refractive index fluctuations inside the flame volume using the CLIV.

5. CONCLUSION

In order to increase the efficiency of modern jet engines or stationary gas turbines, swirl-stabilized flames are used, which need to be optimized by means of the flame transfer function during the industrial development process. For this purpose, a high-speed camera-based laser interferometric vibrometer (CLIV) was proposed for the seedingless measurement of the heat release rate as well as flow velocity inside a flame volume. The CLIV provides high measurement rates up to 40 kHz at a maximum resolution of $256 \text{ px} \times 128 \text{ px}$ with a pitch of $28 \text{ }\mu\text{m}$. The new system was validated using standard LIV for reference measurements at a mechanically vibrating test object at known frequency. Both measurement systems provide a similar system noise and a relative uncertainty of the measured power density of 15 %. Additionally, first measurements of refractive index fluctuations inside a flame volume were shown.

In future experiments, the heat release rate has to be calculated from the measured Doppler frequency and the flow velocity can be achieved by means of correlation of different pixel signals. Finally, the spatio-temporally resolved flame transfer function can be obtained.

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