FUTURE DEVELOPMENTS FOR LASER-INDUCED THERMAL ACOUSTICS

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Introduction

The development of novel flow diagnostic techniques typically proceeds in certain stages-from a proof-of-principle in a laboratory to a commercial product either for use in industry or as turn-key research tool. While the first usable versions are brought to market, further progress is made in the laboratory by improvements, refinements, and extensions of the technique. Consider Particle Image Velocimetry (PIV), which started by double-exposing a photographic film with the image of an illuminated particle-laden flow and where today turn-key, off-the-shelf CCD systems are available for purchase, which include the necessary data analysis software. At the same time, 3d PIV, dual-plane PIV, Doppler Global Velocimetry (DGV), etc. are being used in laboratories and will doubtless be available as integrated systems in the near future.

In this paper, the origin, an overview over the current status and an outlook on the future potential of Laser-Induced Thermal Acoustics (LITA) will be given, where the focus will be on the possible technique extensions to other than the current applications. As such, it represents a collection of ideas and avenues for future research, which have not been applied as of yet, but are conceptually feasible.

Laser-Induced Thermal Acoustics

LITA is a non-intrusive, remote, instantaneous point-measurement technique, originally for the measurement of the speed of sound, and the thermal diffusivity. A coherent, pulsed excitation beam is split in halves, which are focused and intersect path-length matched at a shallow angle in the sample volume (Fig. 1), where an interference fringe pattern is observed. Unlike for Laser Doppler Velocimetry (LDV), the energy of the excitation pulse is sufficient for two physical mechanisms to become important: thermalization and electrostriction. Thermalization denotes the absorption of light energy by the fluid molecules and is represented mathematically as a driving term in the energy equation. Electrostriction describes the acceleration of polarizable molecules in the presence of an electric field gradient. This effect is accounted for by a driving term in the momentum equation. Both effects cause the electric field fringe pattern to result into a density grating. Since the excitation beam pulse is very fast (a few ns), the density perturbations are not stationary, but are in the form of two acoustic waves, which propagate in opposite directions outwards and which interfere constructively and destructively over time. The evolution of the density gratings can be observed by focusing a continuous interrogation beam at the Bragg angle onto the sample volume. Depending on the instantaneous modulation depth of the density grating, part of the interrogation beam (~0.01%) is scattered into a coherent signal beam, whose intensity is recorded by a photomultiplier tube over time (Fig. 2) [1-4].

The time-history of the signal depends on the grating's Brillouin frequency (local speed of sound divided by fringe spacing), the thermal diffusivity and several experimental parameters, such as laser wavelengths and the geometry. The speed of sound and the thermal diffusivity can be extracted from the signal by a least-squares fit of a mathematical model to the data. Typically, the duration of a signal is in the order of 1 μs. If the density grating is convected along its normal vector, the signal beam experiences a Doppler shift, which can be made visible in the

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Abstract

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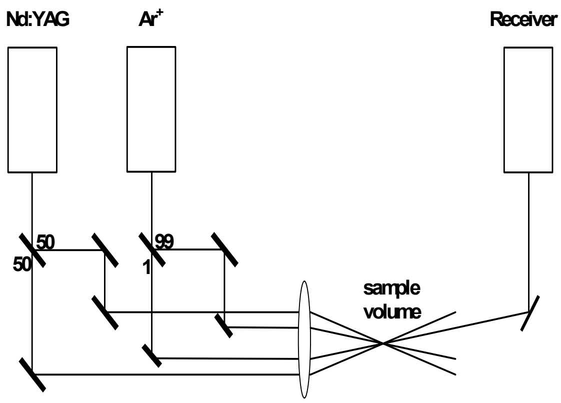

Figure 1: Schematic layout for optical LITA setup. A 50/50 beam splitter splits the excitation beam in halves, which are, path-length matched, focused by a lens onto the sample volume. Shown is the setup for heterodyne detection – a continuous laser beam is split in a weak reference beam and a strong interrogation beam. The reference beam is aligned such that it coincides with the signal beam.

signal by heterodyne detection, i.e., not only the signal beam alone is detected, but the superposition of the signal beam with an unshifted reference beam (see Fig. 1). This information yields the flow velocity and, in connection with the simultaneously measured speed of sound, the Mach number as ratio between the Doppler shift and the Brillouin frequency [5 - 8]. Another possibility for velocimetry using LITA is a laser-two-focus approach, where the interrogation beam is focused at a location slightly downstream of the focus of the excitation beams. The velocity follows from the time delay between the excitation pulse and the detection of the convected density grating by the interrogation beam [9].

Depending on the test gas (mixture) and the laser wavelengths, thermalization and electrostriction have different contributions to the total signal. Because both mechanisms result in different signal shapes, their relative importance can be determined. If the test gas composition and the laser wavelengths are chosen such that only one trace species produces significant thermalization, while all other species are only excited non-resonantly, then the concentration of the trace species can be measured [10]. Theoretically, the speed of sound, the thermal diffusivity, the flow velocity, and a concentration can be measured simultaneously. The temperature can be deduced from the speed of sound if the gas composition is known. The fluid's density can be obtained if the dependence of the thermal diffusivity on the density is known. The Mach number follows directly from the measured speed of sound and the flow velocity.

As nonlinear laser diagnostic technique, it is insensitive to flow luminosity and soot, and the signal levels increase disproportionally with increasing pressure (density), which makes LITA a prime candidate for high-pressure combustion measurements [11] and for hypersonic applications.

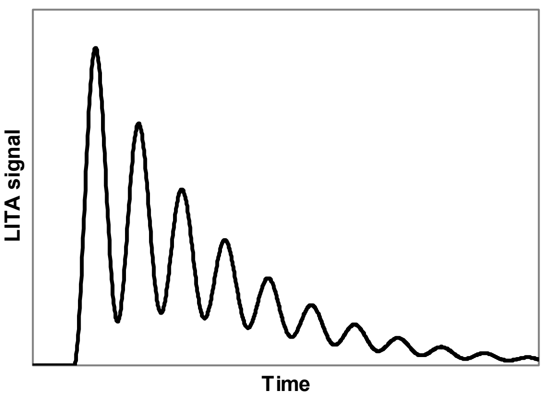

Figure 2: Typical shape of a LITA signal from thermalization. The x-axis spans approximately 1 μs. The frequency of the oscillations is the Brillouin frequency. The decay behavior of the tail is governed by the laser beam half-widths and the thermal diffusivity of the test fluid. Electrostrictive LITA signals oscillate at twice the Brillouin frequency and the values at the minima are close to zero.

Technique refinements

Turn-key LITA systems. LITA requires a significant investment in equipment and time. For most non-reacting and low-speed flows, other techniques exist, which yield more data (planar vs. point) at a lower cost. This restricts the likely applications of LITA to areas where these other techniques are not applicable. Even there, one can not afford to have one scientist only to setup and operate the measurement technique, which should only be a tool, but not the subject of interest. Little can be done on the subject of the required equipment, but the cost of the components will surely decrease over time.

As far as the complexity is concerned, different optical layouts have been used and proposed, some of them even using a calibration arm [12] for improved accuracy, but all these setups require a cumbersome alignment of three or more laser beams, which have to be focused on the same point in space under a given angle. The tolerances are small (tens of µm and fractions of one degree).

Turn-key LITA systems, which are either pre-aligned or which are self-aligning are an important to aid the proliferation of LITA. Two companies, MetroLaser and Advanced Projects Research Inc. (APRI), offer such systems. The MetroLaser product consists of pre-aligned sender and receiver components. In its current version, only thermometry is possible. The APRI product is self-aligning and will allow the measurements of all quantities mentioned in the introduction, i.e., speed of sound, flow velocity, thermal diffusivity, and a species concentration.

Another crucial part for a turn-key system is an improved algorithm for the data analysis, i.e., one that extracts all desired quantities from the signal reliably and without user intervention.

Multi-point measurements. If sufficient pulse energies are available, then instead of intersecting laser beams, intersecting laser sheets can be used. If an interrogation sheet is then used for probing the now linearly stretched sample volume and if multiple detectors are used along the signal sheet, data can be obtained at several points along a line. The signal intensity at each detector is inversely proportional to the spatial resolutio, which is also limited by the data acquisition capabilities, where sampling rates above 100 MHz are typically required for each channel.

The spatial range for this kind of setup will only be in the order of millimeters, but it could offer the possibility of measuring in hypersonic boundary layers, reacting shear layers, or across flame fronts. If multiple simultaneous measurements should be taken over a wider spatial extent, then optics producing multiple distinct laser beams, such as custom diffraction optics, are a more realistic option.

Measurement of multiple velocity components. In its original setup, LDV measures only one component of the velocity vector. By creating different-colored gratings with different spatial orientation in the sample volume, two or even three velocity components can be measured. With a similar modification, LITA can be modified to measure multiple velocity vector components (Fig. 3). Unlike LDV, which relies on incoherent scattering, LITA yields coherent signal beams. Consequently, all excitation laser beams

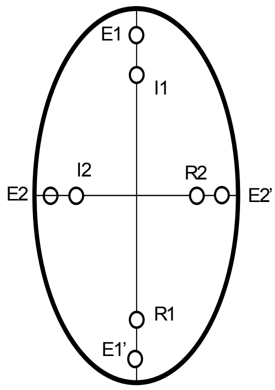

Figure 3: Beam layout for two-component LITA velocimetry. Shown is the laser beam pattern on the focusing lens. Excitation beam E1 and E1' create a horizontal interference grating. Interrogation beam I1 is scattered into signal beam S1 (not shown), which coincides with reference beam R1 behind the sample volume. Its Doppler shift depends on the fluid's velocity component in the vertical direction. Excitation beams E2 and E2' result in a vertical fringe pattern, off which interrogation beam I2 is scattered. The Doppler shift of signal beam S2 then only depends on the horizontal convection velocity component of the gratings.

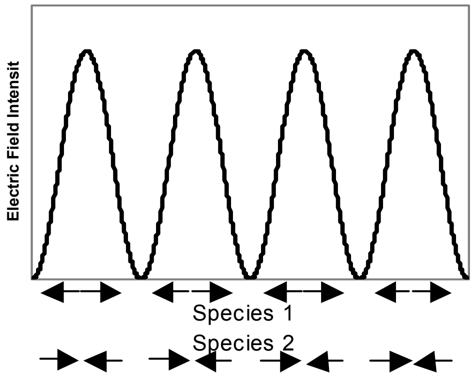

Figure 4: Creation of a species grating through electrostriction. The graph shows the electric field intensity created by the intersecting excitation beams along the cross-section through the sample volume. In the example shown, one species is accelerated towards high electric field intensities, the other in the opposite direction. Note however, that only different electrostriction magnitudes (possibly of equal sign) are required by the two species.

(E1, E1', E2, E2') and all interrogation/reference laser beams (I1, R1, I2, R2) can have the same wavelength so that only two laser sources are required. The Doppler shift of one of the signal beams is proportional to the vertical velocity component, the frequency shift of the second signal beam is proportional to the horizontal convection velocity component of the grating pattern.

Technique extensions

Measurement of mutual species diffusion rates. As long as the excitation pulse is short, e.g. from a Q-switched Nd:YAG laser, electrostriction cannot result in bulk movement of fluid molecules over distances approaching the fringe spacing, which is the shortest characteristic length scale for LITA. Assume now that the laser pulse duration is significant to allow such bulk fluid movements and that furthermore, the fluid is a binary mixture, where the polarizability for the two species is different and that hence the species are migrating at different speeds to the electric field maxima or minima. Using this effect (photophoresis), a species grating is produced (Fig. 4). Photophoresis can also be caused through thermalization through the Soret effect [13] (also known as thermophoresis). Assuming that the two species have different refractive indices, then the species grating will behave similar as the thermal grating, which is produced in the case of thermalization. After the excitation pulse, the inhomogeneities will slowly vanish due to species diffusion (cf. thermal diffusion in thermalization signals). The mutual diffusion coefficient can be determined from the decay rate of the signal.

Measurement of photochemical reaction rates. Consider a test fluid such that a photochemical reaction can be started by sufficient light intensities at the excitation beam wavelength. Then such a reaction will be initiated in the sample volume depending on the local light intensity, i.e., the reaction will be initiated primarily on the fringes of the interference grating. As in

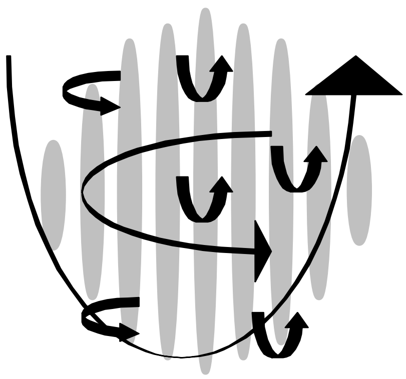

Figure 5: Different turbulent length scales interact with the evolving density grating. While small eddies cause an accelerated decay of the coherent structures, larger eddies convect the entire grating along with them out of and back into the sample volume. The density behaves like a passive scalar in incompressible flows, but nonlinear interactions are observed in compressible flows. By measuring the observed eddy diffusivity for different fringe spacings, the turbulent length scales may be found. The fringe spacing is easily controlled by changing the beam crossing angle.

the case of the Soret effect, a species concentration grating develops. Here, however, the chemical reaction continues even after the end of the excitation pulse. In particular, the reaction will also propagate into regions where the reaction had not been initiated. Assuming an appropriate model, the signal shape can be related to the reaction kinetics.

Measurement of turbulent length and time-scales. The effect of turbulence on the density grating depends on the turbulent length and time scales (Fig. 5). Small eddies (size in the order of the fringe spacing, a few μm) will accelerate the decay of the coherent structures through the effect of the eddy diffusivity. This leads, like the thermal diffusivity, to accelerated signal decay. The eddy diffusivity can then be measured as excess of the measured diffusivity over the known thermal diffusivity. The such measured eddy diffusivity will depend on the fringe spacing of the density grating. By repeated measurements of the eddy diffusivity for different fringe spacings, it might be possible to measure the turbulent length scales. These effects will only be observable if the turbulent time scales are shorter than the grating lifetime (~1 μs).

Conclusions

Laser-Induced Thermal Acoustics is still at the early stages of its development. First commercial turn-key systems are just appearing on the market. Meanwhile, laboratory applications have already discovered additional applications and capabilities. This is not the end of the chain, but yet more possibilities have been presented in this paper. They ranged from refinements within its classical application, flow measurements, to technique extensions to reaction kinetics, physical chemistry, and turbulence research. All of them require a mathematical model to relate the LITA signal shape to the new measurement quantities. These can be derived following the roadmap given in the literature [1]. Progress will also be governed by the advances in laser, detector, and data acquisition technologies. For example, when pulsed low-coherence laser sources are available at sufficient power levels, they may be used to improve the spatial resolution (depth of the sample volume) of LITA.

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