Nonlinear Tomography: A New Imaging Theory for Combustion Diagnostics

非線形トモグラフィー：燃焼解析のための新たなイメージング理論

Weiwei CAI

“Tomography” is a technique for obtaining internal information of the target to be measured. Its application to gas concentration measurement will aid in determining the spatial distributions of gas concentrations in combustion diagnostics. However, the classical tomography can only be applied to the situation where pressure is constant and uniform cross the flow field. Also, only one component can be obtained with limited sensitivity due to the inherent limitations with classical tomography. The combination of the newly proposed concept “Nonlinear Tomography” with the latest laser gas measuring techniques will enable the simultaneous spatial distribution analysis of the multiple parameters including temperature, pressure, and concentration of several gas components. This will facilitate the study of new combustion concepts and engine designs.

Background

Combustion is still the dominant form of energy production in the world and the development of clean combustion technologies are thus of vast socioeconomic importance[1]. Since few alternatives exist in many applications, e.g. transportation, combustion will continue to be a key technology for the foreseeable future. Thus, the full understanding and effective control of combustion processes are of paramount importance to increase energy efficiency, reduce pollutant production (NO_x, SO_x, and greenhouse gases), and for the safe operation of combustors such as power plant boilers and aerospace engines. A crucial requirement here is to understand the coupling of complex reaction processes with fluid dynamics, chemical kinetics, and heat transfer. This requires the quantitative measurement of a number of parameters such as temperature, species concentration, and equivalence ratio – all are physically accessible with modern laser sensing technologies that are non-invasive and can fully preserve the original flow fields.

Absorption Spectroscopy and Classical Tomography

Laser Absorption Spectroscopy (LAS) is one of the most widely adopted tools for combustion scientists due to its ease of implementation, species-selectivity, capabilities of measuring multiple flow parameters (e.g. temperature, species concentration, pressure, and velocity)[2, 3], and high-sensitivity when combined with cavity-enhanced techniques[4-7], modulation methods[8-10], or photoacoustic spectroscopy[11]. Unfortunately, absorption spectroscopy is a Line-of-Sight (LOS) technique, which reflects only averaged properties along the laser path without providing any spatially-resolved information. However, the optimization and maturation of modern combustion concepts such as Homogeneous Charge Compression Ignition (HCCI), Reactivity Controlled Compression Ignition (RCCI), and Pressure Gain Combustion (PGC)[1] require full spatial and temporal resolutions of the flow field. Because of this, laser imaging techniques have become indispensable tools for the spatially-resolved measurements of flow fields and can generally be divided into two categories, which are planar imaging techniques and tomography, respectively. In the planar imaging techniques, laser radiation is redirected away from its original propagation direction toward the detector (typically a camera) through mechanisms such as elastic scattering, inelastic scattering, florescence, phosphorescence, etc. The detected signals on the camera directly reflect the light intensity distribution on the imaging plane. On the contrary, in tomography the detectors are arranged on the laser propagation direction;

and because of this, LOS absorption techniques can be combined with tomography, not only maintaining their original advantages but also at the same time enabling the spatial resolution.

Officially, classical tomography is defined as reconstruction of a field from the set of its line integrals. For tomography based on Direct Absorption Spectroscopy (DAS), the field is absorption coefficient at a specific transition and a typical line integral along the LOS is the overall absorbance. In classical tomography, a set of LOS measurements along the same direction but at different locations is termed a projection. In discretized domain, each LOS measurement essentially provides a linear equation whose variables are the absorption coefficients of the pixels probed by the laser beam[12]. By sampling the flow field at different locations and along various directions, a set of linear equations can be obtained, the solution of which is the distribution of absorption coefficients at the target transition across the Region of Interest (ROI). The results can then be post-processed according to the Beer-Lambert law to obtain flow parameters such as temperature and species concentration, which are the determinant factors of the absorption coefficient. It has to be noted that before the development of nonlinear tomography which will be introduced below, DAS was the only absorption technique that had been adopted in classical tomography.

However, the classical absorption tomography suffers from several critical disadvantages including 1) limited temporal resolution due to the requirement of intensive spatial sampling of the flow field through angular sweeping (just like the CT scan one would get in a hospital), making them unsuitable to trace transient phenomena in turbulent flows; 2) assumption of uniform pressure profiles, which is not true in some scenarios such as the supersonic flows within a scramjet where prevailing shock waves lead to dramatic pressure drops due to non-uniform and localized heat release; 3) limited sensitivity with single-path LOS measurements; and 4) difficulties in baseline fitting at high pressure situations where adjacent absorption features interfere severely. These drawbacks have greatly hampered the applications of the absorption-based tomography to combustion diagnostics.

The defect in temporal resolution roots deeply in the nature of classical tomography, which only relies on sampling in the spatial domain. In order to obtain sufficient information about the flow field and permit a successful tomographic reconstruction, LOS measurements have to be taken along numerous directions using either parallel or fanned beam arrangements, both require mechanical means for angular beam displacement[12]. On the other hand, the remaining limitations are inherited from DAS. Unfortunately, more advanced absorption techniques e.g. Wavelength Modulation Spectroscopy (WMS)[13], which is immune to those limitations, cannot be combined with classical tomography since its signals are not line integrals of any physical field. However, the overcome of those limitations are necessary for many reasons. For example, the pressure distribution relates directly to thrust and highest Mach numbers achievable in a scramjet; and the detection of minor species such as C_2H_2 with sensitive techniques is crucial to study the formation of soot in biomass flames[14]. Thus, there is a strong motivation to develop a novel tomographic theory.

Concept of Nonlinear Tomography

Stimulated by the motivation mentioned in the previous section and enlightened by the latest development in octave-spanning Supercontinnum (SC) generation[15] and calibration-free WMS[13], the author recently proposed a new theory – nonlinear tomography. In difference to classical tomography, which samples only the spatial domain at a single transition, this new approach manages to incorporate an additional (i.e. spectral) domain in both the tomographic sampling and reconstruction processes. Experimentally, it means for each LOS measurement, multiple absorption transitions can be probed almost simultaneously using chirped SC radiation. Mathematically, it means for a single LOS measurement, the number of equations scales linearly with the number of transitions detected. In classical tomography, the equations are considered as linear when the absorption coefficients are assumed as the variables. Because of this, the classical tomography is also referred to as linear tomography. Unfortunately, in linear tomography, these equations are not simultaneous since the absorption coefficients are not the same for different transitions and accordingly the number of variables also scales up. On the contrary, in nonlinear tomography, temperatures and species concentrations are directly assumed to be the variables, circumventing the step of solving for absorption coefficients. In this case, a set of simultaneous nonlinear equations is obtained (where the name comes from).

Figure 1 illustrates a typical nonlinear tomography system, in which a hyperspectral (ultra-broadband) laser is split into multiple beams to map out the flow field. Due to the absorption, the intensity of the laser will be attenuated and recorded by the photo detectors. The attenuation can then be converted to absorbance according to the Beer-Lambert law. Since the chemicals

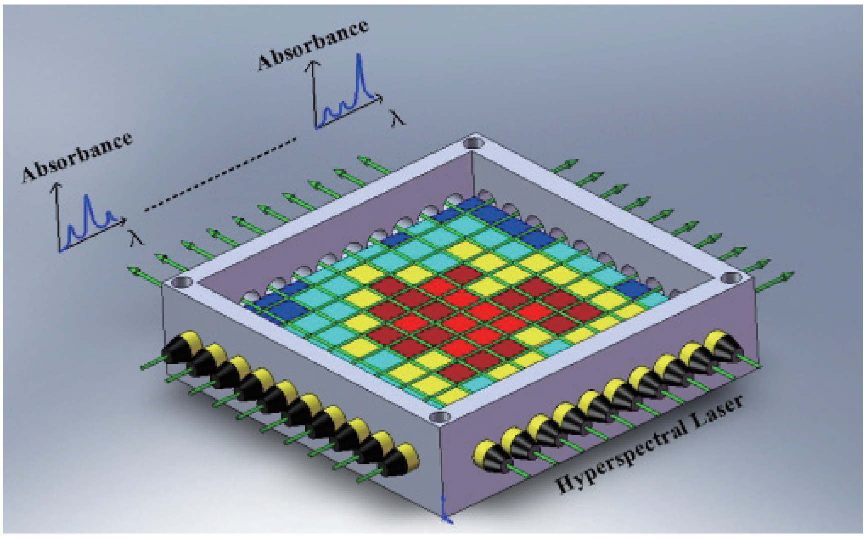


Figure 1 Illustration of nonlinear tomography with a hyperspectral laser.

in the flow absorb different amount of the light for distinct color, a curve of absorbance versus wavelength i.e. absorption spectrum can then be obtained for each laser beam. The wavelengths with strong absorption can then be selected for tomographic reconstruction to simultaneously recover the distributions of parameters such as temperature, concentration of multiple species, and pressure.

Compared with its linear counterpart, nonlinear tomography features several unprecedented advantages including 1) the number of projections can be greatly reduced since the incorporation of spectral dimension effectively increases the sampled information; 2) the small number of projections can be fixed, removing the mechanical part and increasing the temporal resolution to MHz domain; 3) pressure imaging can be realized by also setting the pressures as the variables in the nonlinear equation system; and 4) signals are no longer required to be line integrals of any field, and thus enabling the adoption of more advanced absorption techniques such as WMS to increase the detection sensitivity.

Absorption–based Nonlinear Tomography

With the aid of nonlinear tomography, the author has proposed two novel tomographic variants to help solving long-standing combustion problems. These two techniques are the so-called Frequency-Agile Tomography (FAT)[16] and Multiplexed Absorption Tomography (MAT)[17] respectively.

The motivation for inventing FAT originated from the aerospace engine industry. For example, the Rose Royce in UK, currently they are developing the next-generation scramjets, within which the pressure fields are not uniform and also the combustion processes happen at a microsecond time-scale. This requires a technique with not only pressure resolution but also sufficient temporal resolution, which are not possible with the existing imaging methods. On the other hand, FAT is the perfect candidate to do the job and its development was enabled by the latest advancement in SC generation with the all-normal dispersion photonic crystal fiber[15], which enhances shot-to-shot stability 100× than commercially available SC source, making single-shot ultra-broadband absorption spectroscopy feasible. It was demonstrated that two fixed orthogonal projections are sufficient for a successful reconstruction in FAT, not only reducing experimental costs but also increasing temporal resolution into the MHz domain. Due to the broadband nature of the SC source, the simultaneous imaging of multiple species becomes possible.

Unfortunately, all previously mentioned tomographic concepts including FAT were based on the DAS; and hence disadvantages inherent to DAS are also inherited by their tomographic counterparts. WMS, on the other hand, does not suffer these drawbacks and enjoys several critical advantages compared to DAS[13], including: 1) improved sensitivity due to improved (10-100×) Signal-to-Noise Ratios (SNR); 2) immunity to laser intensity fluctuation caused by e.g. soot scattering and window fouling; and, 3) avoidance of the baseline fitting requirements, essential for, but difficult to achieve, in DAS applied to high pressure scenarios. Due to these advantages, WMS has been extensively adopted for industrial applications[18, 19]. Compared with SC radiation, tunable semiconductor lasers can be easily modulated with almost linear response via variation in injection current. However, WMS is also limited by its LOS nature and can only be applied to uniform flames. Thus, MAT

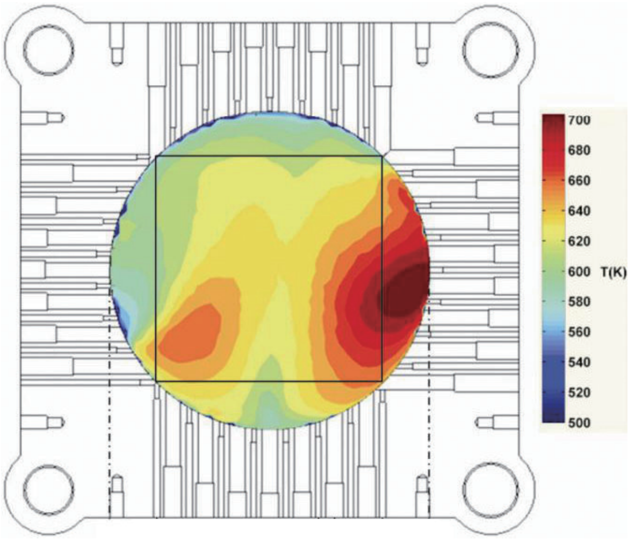


Figure 2 Structure of an engine spacer ring which can be used to install the sampling laser beams. Example temperature distribution within an HCCI engine is plotted in the middle.

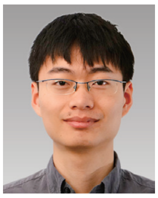
was developed to combine the advantages of nonlinear tomography with calibration-free WMS using tunable semiconductor lasers, pushing the application limit of absorption-based tomographic techniques to harsh combustion environments such as high pressure (up to 100 atm) in a HCCI engine[1] and on-road/in-flight engine tests suffering from vibration, etc. Figure 2 shows a typical structure of an engine spacer ring that can be integrated into the engine to deliver and collect the laser beams for tomographic measurements. Example temperature profile is superimposed in the middle to show the non-uniformities in the flow field.

Conclusion

It has been shown that nonlinear tomography is a powerful theory that can be combined with those representing the most recent progresses in laser technologies and absorption spectroscopy to facilitate the development of modern combustion concepts. The future work includes the further exploration this new theory by developing appropriate techniques to better suit the needs arise from combustion studies. For example, 3D measurements are highly desirable both for fundamental combustion research and *in situ* monitoring of combustors such as automotive or aerospace engines. However, it is almost impractical to realize with linear tomography due to the large number of projections required, which are financially formidable. Fortunately, 3D imaging is possible and affordable with the aid of nonlinear tomography.

References

[1] Yiguang, J., “Recent progress and challenges in fundamental combustion research”. *Prog. Mech.*, **44**, 201402 (2014)
[2] Li, F., et al., “Uncertainty in velocity measurement based on diode-laser absorption in nonuniform flows”, *Appl. Opt.*, **51(20)**, 4788 (2014)
[3] Allen, M.G., “Diode laser absorption sensors for gas-dynamic and combustion flows”, *Meas. Sci. Technol.*, **9(4)**, 545 (1998)
[4] Laurila, T., et al., “A calibration method for broad-bandwidth cavity enhanced absorption spectroscopy performed with supercontinuum radiation”, *Appl. Phys. B*, **102(2)**, 271 (2014)
[5] Langridge, J., et al., “Cavity enhanced absorption spectroscopy of multiple trace gas species using a supercontinuum radiation source”, *Opt. Express*, **16(14)**, 1017 (2008)
[6] Watt, R.S., et al., “Cavity Enhanced Spectroscopy of High-Temperature H_2O in the Near-Infrared Using a Supercontinuum Light Source”, *Appl. Spectrosc.*, **63(12)**, 1389 (2009)
[7] Qu, Z., et al., “High sensitivity liquid phase measurements using broadband cavity enhanced absorption spectroscopy (BBCEAS) featuring a low cost webcam based prism spectrometer”, *Analyst*, **138(21)**, 6372 (2009)
[8] Rieker, G.B., J.B. Jeffries, and R.K. Hanson, “Calibration-free wavelength-modulation spectroscopy for measurements of gas temperature and concentration in harsh environments”, *Appl. Opt.*, **48(29)**, 5546 (2009)
[9] Li, H., et al., “Extension of wavelength-modulation spectroscopy to large modulation depth for diode laser absorption measurements in high-pressure gases”, *Appl. Opt.*, **45(5)**, 1052 (2006)
[10] Nikodem, M., D. Weidmann, and G. Wysocki, “Chirped laser dispersion spectroscopy with harmonic detection of molecular spectra”, *Appl. Phys. B*, **109(3)**, 477(2012)
[11] Tennal, K., G.J. Salamo, and R. Gupta, “Minority species concentration measurements in flames by the photoacoustic technique”, *Appl. Opt.*, **21(12)**, 2133 (1982)
[12] Kasyutich, V. and P. Martin, “Towards a two-dimensional concentration and temperature laser absorption tomography sensor system”, *Appl. Phys. B*,**102(1)**, 149 (2011)
[13] Sun, K., “Ultilization of multiple harmonics of wavelength modulation spectroscopy for practical gas sensing”, 2013, Stanford University.
[14] Koziński, J.A. and R. Saade, “Effect of biomass burning on the formation of soot particles and heavy hydrocarbons”, *An experimental study. Fuel*, **77(4)**, 225 (1998)
[15] Dupont, S., et al., “Low noise all-normal dispersion PCF utilised for rapid sweeping spectroscopy”, *Laser Phys. Lett.*, **11**, 075601 (2014)
[16] Cai, W. and C.F. Kaminski, “A tomographic technique for the simultaneous imaging of temperature, chemical species, and pressure in reactive flows using absorption spectroscopy with frequency-agile lasers”, *Appl. Phys. Lett.*, **104(3)**, 034101(2014)
[17] Cai, W. and C.F. Kaminski, “Multiplexed absorption tomography with calibration-free wavelength modulation spectroscopy”, *Appl. Phys. Lett.*,: p**104(16)**, 154106 (2014)
[18] Zeller, W., et al., “DFB Lasers Between 760 nm and 16 μm for Sensing Applications”, *Sensors*, **10(4)**, 2492 (2010)
[19] Ren, W., “Mid-infrared laser diagnostics for chemical kinetics study of oxygenates”, 2013, Stanford University.



Weiwei CAI
Department of Chemical Engineering
University of Cambridge
European Union Marie Curie Fellow
Ph. D