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Optical diagnostics for high-speed flows

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ABSTRACT

Since 2000 there has been a revolution in diagnostics of high-speed air flows. The foundations for this revolution were laid over the past few decades, but with the development of new short pulse and pulse burst laser technologies, higher laser powers and higher pulse energies, new high-speed cameras, better laser control and improved detection and laser delivery methodologies, many very effective new capabilities have been developed. Newly developed methods for molecular tagging velocimetry provide high fidelity visualization of transport properties and may be extended to simultaneous temperature measurements. Rapid field imaging with frequency tunable pulse burst lasers shows instantaneous flow structure and complex boundary and mixing interactions. Extending these pulse burst concepts to swept volumetric imaging is very promising for full volumetric data collection. Fast wavelength modulation spectroscopy follows real-time flow variation, and three-dimensional particle imaging extends particle imaging velocimetry to volumetric data acquisition.

1. Introduction and retrospective

The use of optical diagnostics for the study of high-speed flows dates back to the 1800s when shadowgraphs and schlieren yielded images of the bow shocks, Mach disks and other structures associated with high-speed projectiles and supersonic flows [21] (see Fig. 1). Notable progress in optical diagnostics through the twentieth century that did not involve laser technologies primarily focused on further development of schlieren and shadowgraph for high sensitivity and high-resolution imaging of flow structure. These approaches provided good resolution of large-scale structures but suffered from integration over the full optical path length, so details of turbulent boundary layers, curved and unsteady shocks and mixing structures were not well resolved. The introduction of an electron beam [30] overcame that problem since electron beams could be spatially collimated and electronically swept, providing luminous cross sections of shock and boundary layer structure. However, electron beams are limited to low density flows due to electron scattering, and they are very difficult to integrate into a test facility. Focusing schlieren [55] provided a method for imaging flow structure over a reduced integrated path length in higher density flows.

Since the invention of the laser in 1960, the continuing evolution of optical flow diagnostics has been driven in large part by ever-increasing laser and camera capabilities. The very first laser invented, the pulsed ruby laser, provided high energy and excellent coherence, which enabled the development of interferometric methods to measure flow field properties, such as flow velocity using seed particles [54] and the imaging of boundary layer structure using density variations [16]. It was not until after the invention of the frequency tunable laser in 1966 [50,48] that atomic and molecular spectroscopy could be utilized for diagnostics. The tunable dye lasers only operated efficiently in the visible portion of the spectrum where the air is highly transparent, so for these new applications, flow seeding became important. Initially seeding with sodium provided planar imaging of flow cross sections [33] and enhanced schlieren [4]. These advances were accomplished by tuning the laser either onto a resonance or near a resonance and utilizing the laser-induced fluorescence for imaging planar cross sections or the enhanced index of refraction for higher sensitivity schlieren. Tuning the lasers provided methods for imaging and measurement of velocity fields by taking advantage of the Doppler shift associated with the motion of the gas [58]. Due to the reactivity of sodium with air, these experiments were carried out in either helium or nitrogen flows. Imaging and interferometry in these early experiments were done with conventional hard film.

Molecular iodine was subsequently used for laser-induced flow imaging [29] since it has spectral features throughout the visible and does not react with air. Later, tunable ultraviolet lasers became available through frequency up conversion of nanosecond laser-driven pulsed dye lasers, and nitric oxide [41] and acetone [25] became the preferred molecular species for seeding. CCD array and intensified CCD cameras became available and provided high sensitivity, time gating and convenient data processing capabilities.

The possibility of using nonlinear optical methods for flow diagnostics became credible with higher energy, frequency tunable

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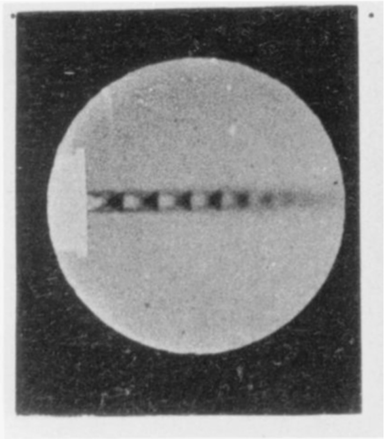

Fig. 1. Image of an underexpanded sonic jet taken with schlieren photography [26]

pulsed lasers and led to temperature and species measurements by Coherent Anti-stokes Raman Scattering (CARS), temperature and velocity measurements by Laser Induced Thermal Anemometry (LITA) and Molecular Tagging Velocimetry (MTV). The CARS approach [27,18] brings two or three pulsed laser beams together at a point and, through a resonant nonlinear interaction, generates a new laser beam whose intensity is determined by the properties of the gas at that point. CARS has the capability of measuring species concentrations as well as temperature. For that reason it is also of great interest for combustion studies. Originally CARS required that at least one of the lasers be scanned in frequency to acquire the data, and that meant that CARS could only be used for time averaged measurements. Broadband and later dual broadband CARS [14] solved that problem by replacing the scanned laser with a broadband laser and separating the multiple CARS signal frequencies that were simultaneously generated with a spectrometer. This allowed CARS to capture full spectral data over a limited band in a single pulse.

LITA [9] was a similar local measurement approach. It used a pair of focused lasers to produce a localized thermal grating into the air through nonlinear mixing, and a probe laser to follow the motion of the acoustic waves created by that grating as they interfered with each other. This provided a local measure of the temperature though the speed of sound and a measure of the flow velocity through frequency offsets associated with the flow motion.

MTV [20] introduced a line or array of lines into the flow and tracked them in time as they moved, providing a measure of both the velocity and the flow velocity structure. The first MTV concept implemented in unseeded air was Raman Excitation+Laser Induced Electronic Fluorescence (RELIEF) [34], which used three laser beams – two to drive the oxygen into the vibrational state through stimulated Raman excitation, and one to interrogate the displaced line or pattern by laser-induced fluorescence. Its great feature was that it did not require seeding of the air with other molecular species and produced negligible perturbation. It worked well because of the relatively long lifetime of the oxygen vibrational state (many microseconds even in humid air). It was limited by the complexity of the laser systems. Its success led to the development of other approaches including laser-induced Ozone Tagging Velocimetry (OTV) [44], which was also used as a tag in unseeded air. In this case, the ozone was created by a chemical reaction following laser-induced dissociation of molecular oxygen. The motion was tracked by subsequent laser-induced dissociation of the ozone and imaging of the fluorescence from the excited molecular oxygen fragment. Other MTV approaches for air developed before the 2000 used seed molecules and included biacetyl [17] and water vapor [5]

Single mode, frequency tunable lasers utilizing injection locking enabled the development of molecular, atomic and etalon filtered technologies, permitting strong suppression of background scattering [35], imaging of air temperature, velocity and density (Filtered Rayleigh Scattering [36]) and velocity imaging by Doppler shifted particle imaging through an iodine filter (Doppler Global Velocimetry [31]) as well as velocity and temperature imaging of Doppler shifted Rayleigh scattering through an etalon [49]. Single mode tunable diode lasers derived from the communications industry and augmented by wavelength modulation technology have also opened the door to diagnostic methods for air based on direct absorption spectroscopy using very weak near infrared lines in molecular oxygen [43]. This concept has been successfully implemented for density, velocity and temperature measurements based on the measurement of extinction, line shifts and line broadening.

Particles have been used for centuries to observe flows, but the development of laser provided a method for quantitative measurement through instantaneous holographic imaging and other interferometric methods. Much early work focused on Laser Doppler Anemometry (LDA) [13] with continuous lasers for one or two component point measurements of flow velocity, in which two laser beams intersected at the sample point and the scattering of the particle as it moved through the interference pattern which was created provided the measure of velocity. With four crossing beams, two velocity components could be measured. The development of high power nanosecond pulsed lasers enabled imaging of time frozen particle fields and this led to particle imaging velocimetry (PIV) [1], where the two-dimensional velocity field was measured by the displacement of the particles captured with double pulsed laser systems. Digital PIV [56] was enabled by the development of high-resolution CCD cameras and eliminated the need for hard film.

Thus at the beginning of the twenty-first century many capabilities existed for optical diagnostics of high-speed flows. Since that time further development and implementation of these capabilities have occurred and laser technology has significantly advanced, enabling new approaches. In addition to achieving higher pulse energy, better reliability and higher efficiency lasers, optical fiber technologies, new cameras, frequency tunable pulse burst lasers and sub-picosecond lasers have opened up new possibilities for diagnostics. With these tools major advances have been made in high-speed imaging, molecular flow tagging, wavelength modulation spectroscopy, Particle Imaging Velocimetry, Coherent Antistokes Raman Scattering and Rayleigh scattering.

2. Imaging

Laser Rayleigh scattering is the strongest non-resonant light scattering process available for air measurements, but the low scattering cross section of air molecules has made its use for high-speed diagnostics challenging and only recently practical with high energy pulsed lasers and high sensitivity, time gated cameras. It is best applied in free jet facilities where background scattering can be minimized. An important application of Rayleigh scattering in an free jet of air was the evaluation of the Mariah II/Radiatively Driven Hypersonic Wind Tunnel concept [39]. Those tests were undertaken for the validation of computational models of an electron beam heated hypersonic ground test facility and were conducted at Sandia National Laboratory using their 1 MW Hawk electron beam facility [28]. The configuration for the tests is shown in Figs. 2 and 3. The 1 MW electron beam is steered and focused into the nozzle from downstream using a carefully contoured magnetic field and the Rayleigh imaging is performed with a frequency doubled Nd:YAG laser focused to a thin sheet along the center line of the flow at the exit of the nozzle, providing