Pressure Measurement in Supersonic Air Flow by Differential Absorptive Laser-Induced Thermal Acoustics

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Abstract

Nonintrusive, off-body flow barometry in Mach-2 airflow has been demonstrated in a large-scale supersonic wind tunnel using seedless laser-induced thermal acoustics (LITA). The static pressure of the gas flow is determined with a novel differential absorption measurement of the ultrasonic sound produced by the LITA pump process. Simultaneously, stream-wise velocity and static gas temperature of the same spatially-resolved sample volume were measured with this nonresonant time-averaged LITA technique. Mach number, temperature and pressure have 0.2%, 0.4%, and 4% rms agreement, respectively, in comparison with known free-stream conditions.

OCIS codes: 280.2490, 280.7250, 120.7250

Laser-induced thermal acoustics (LITA)[1] is one of many optical diagnostics under development for noninvasive flow measurement. LITA velocity[2-5] and temperature[4-6] measurements in subsonic flows have been reported; however little has been done supersonically[7] because gas densities and LITA signals are greatly reduced compared to

subsonic flows. Additionally, practical pressure measurements with LITA have not yet been demonstrated in any speed region. A pressure diagnostic[8] has been demonstrated in NO_2-seeded still air, but only over the 300-4000 kPa range (3-40 atm). These large pressures are not common in supersonic wind tunnels, where pressures of 0.1-100 kPa are more typical. The method of Ref. 8 is not practicable for pressures $\leq$ 100 kPa, because sound absorption is greatly increased at lower pressures.

In the present work, remote, non-contact, non-spectroscopic pressure measurements are demonstrated in 10-kPa airflow by extending seedless LITA velocimetry into the Mach 2 supersonic regime. This pressure measurement is possible because of the supersonic nature of the flow and is based on a novel differential absorption measurement (described below) of the laser-induced ultrasonic wave. Along with pressure, temperature and velocity are also determined from the raw LITA data, thus a simultaneous velocity, temperature and pressure measurement is presented here.

In nonresonant LITA, two crossed beams from a 10-nsec pump laser create two counter propagating acoustic plane wave packets in the medium by electrostriction. Illumination of these traveling wave packets (i.e., density gratings) with a second probe laser, at frequency Ω_L, generates a Bragg-diffracted signal beam that consists of two overlapped and co propagating components that are spectrally distinct. These two components are distinguished by their different Doppler shifts $\pm \Delta\omega$ determined by the counter propagating geometry of the two acoustic wave packets. The beating together of the two separate components, at frequencies $\Omega_L \pm \Delta\omega$, produces a modulation of this Bragg-diffracted signal beam at frequency $2\Delta\omega$. If the sound wave reciprocal

wavelength is Δk (i.e., wave vector difference of the two pump beams), the two Doppler shifts are $\Delta\omega = \Delta k \cdot (\pm V_S)$, where $\pm V_S$ are the velocities of the two counter propagating wave packets and $|\pm V_S|$ = the speed of sound (bold-faced quantities denote vectors).

Measurement of the beat frequency $2\,\Delta\omega$, with the known grating wavelength $1/\Delta k$, yields the sound speed. If the mass composition of the fluid is known, translational temperature T is also determined since $T \propto V_S^2$. If the medium is in motion at velocity V_F (assumed to be parallel to Δk and V_S) the frequencies of the signal beam are shifted to $\Omega_L + \Delta k \cdot (V_F \pm V_S)$, but the difference frequency $\Delta\omega$ and the beating are unchanged.

The bulk fluid motion at velocity V_F is also readily obtained from LITA. With a heterodyne approach,[3-5] a local oscillator beam at the probe frequency Ω_L and with optimum intensity is introduced collinearly with the diffracted signal beam such that both are incident on the same detector. The local oscillator mixes nonlinearly with the original signal, and the detected signal then shows modulation at three frequencies: $2\,\Delta\omega$ and $\Delta\omega \pm (\Delta k \cdot V_F)$. The measured frequency at $2\,\Delta\omega$ still gives V_S and T, while V_F is derived from the measured frequency difference, $2\,\Delta\omega'$, of the two new components, where $\Delta\omega' = \Delta k \cdot V_F$. The signal is digitized, and the frequencies can be extracted by a variety of methods. Thus $V_S = \Delta\omega\,/\,\Delta k$, $T \propto V_S^2$, and $V_F = V_S\,\Delta\omega'\,/\,\Delta\omega = \Delta\omega'\,/\,\Delta k$. It is time consuming and difficult to maintain the delicate optical alignment with this traditional version of heterodyne detection. Traditional heterodyne systems lack a "set-and-forget" robustness necessary for non-laboratory applications.

In the present work, we used a new heterodyne approach[9] that greatly improves the robustness of traditional heterodyned LITA, valuable in challenging wind tunnel environments with moderate noise and vibration levels. Even in benign laboratory environments, this common-path optical design reduces the amount of repetitive alignment necessary with the typical multiple-beam heterodyne setup. This method also clearly provides directionality of the velocity measurement. In brief, this version works by imaging the moving gas density gratings onto a fixed Ronchi ruling, providing the same spectral information of the traditional approach, plus flow direction.

With the heterodyne approach, sound speed, temperature, and one component of fluid velocity are determined simultaneously (with a single laser shot) in a measurement time ~ 1 μs. This is possible[4] for subsonic flows with air densities of one amagat, where the heterodyne signals scale linearly with gas density. For the supersonic flow results presented here, the LITA signal strengths were reduced due to the low air densities of 0.1 amagat, and the signal-to-noise (SNR) ratio was poor. Thus, signal averaging over 500 laser pulses (30 Hz) was used in the present low-density work.

Pressure is related to amplitude information and is more difficult to measure than temperature or velocity (both depend on temporal information). Diffracted LITA signal strengths scale with the intensity of the sound packets, which exhibits a pressure-dependent exponential absorption in air. The observed decay of the signal is a convolution of the acoustic absorption with the transit time effect of the finite size laser beams. Thus pressure is measurable by determining the shape of the LITA signal decay. At higher pressures ($\geq$ few atm) the acoustic decay time is large relative to the transit time decay and is easily measurable. This approach has been demonstrated[8] in the 300-

4000 kPa regime, but does not work at smaller pressures (e.g., 10 kPa) because faster

sound decay makes the transit time effect dominant.

However, with supersonic flow at Mach number M, another solution is available.

Two identical wave packets are created instantaneously at time t_o, and in the co-moving

fluid reference frame they counter propagate symmetrically about the creation point. In

the wind-tunnel reference frame, the two wave packets are swept downstream in the same

direction, but at different speeds as shown in Fig. 1. The key idea in this measurement is

that the two packets travel through different path lengths (x_+ and x_-) at identical speeds

(Mach 1) in the comoving supersonic fluid reference frame, although they travel the same

pump-probe distance x_o at different speeds (Mach M+1 and M-1) in the wind-tunnel

frame. By purposefully offsetting the probe beam slightly downstream of the pump

beams, one observes two distinct signals with intensities A_+ and A_-. At times t_+ and t_-, the

fast and slow packets transit the probe beam and sequentially scatter their respective

signals into the detector. The difference in the two signal strengths results from different

acoustic absorptions, since the two wave packets require time intervals $t_+ - t_o$ and $t_- - t_o$ to

propagate distance x_o to the probe beam.

Beer's law, applied to the acoustic wave packets over the path difference $x_+ - x_-$

with pressure P and absorption coefficient α, gives a LITA signal ratio of

$$A_- / A_+ = \exp(-\alpha V_s (t_- - t_+)). \qquad (1)$$

For the temperature range 200-400 K and sound frequencies of 5-10 MHz, we use a

rotational-classical absorption (vibration is ignored) of the form[10]

$$\alpha \propto \Delta\omega^2 T^{0.5} / P \propto \Delta k^2 T^{1.5} / P \qquad (2)$$

which is based on Sutherland's viscosity law. Writing the interval $t_- - t_+$ in terms of flow

Mach number M, temperature T, and pump-probe separation x_o, we rewrite Eq. 1 as

$$P \propto x_o T^{1.5} / [(M^2 - 1)\ln((f_+ A_+ / f_- A_-)^{.5})], \qquad (3)$$

where A_+ and A_- are the area-integrated LITA signal intensities, after fast Fourier

transforming the temporal waveforms. Mach number and temperature are required to

derive pressure from Eq. 3, but they are conveniently supplied by the measured intervals

$t_+ - t_o$ and $t_- - t_o$. Multiplication of the ratio A_+ / A_- by the frequency ratio f_+ / f_- in Eq. 3

corrects for the difference in transit times of the two wave packets as they pass through

the probe beam, where $f_\pm = \Delta \mathbf{k} \bullet (\mathbf{V_F} \pm \mathbf{V_S})$. Outside of the 200-400 K or the 5-10 MHz

ranges, absorption coefficients differing from Eq. 2 may be more accurate.

The common path setup that was used here has been previously[9] described. We

modified the setup of Ref. 9 by offsetting the probe beam downstream of the crossed

pumps to optimize collection of the reflected signals from the acoustic Bragg gratings as

they are swept downstream. A schematic of the beam geometry is shown in Fig. 1. The

overlap region for the two pump beams is about 0.25 x 0.25 x 10 mm, and the pump-

probe stream-wise separation x_0 is about 1/2 mm ($t_+ - t_- \sim 1$ μsec). Measurements were

made in NASA Langley's Unitary Plan Wind Tunnel (UPWT), a large-scale (1.3 x 1.3-

meter test section) closed-circuit supersonic facility. This tunnel has been widely used

for 50 years, and the flow conditions are relatively well known.

Results of free-stream measurements are summarized in Fig. 2. Simultaneous stream-wise Mach number, static temperature and pressure (i.e. the temperature and pressure measured in the moving fluid frame of reference) are shown in Fig. 2(a), 2(b), and 2(c) respectively. LITA measurements are plotted on the vertical axes, against the UPWT values on the horizontal axes. In each case, the solid lines represent perfect agreement between the two techniques. The values supplied by the UPWT are derived from Pitot-probe measurements made during the calibration[11] of the facility. Uncertainties for these LITA data can be estimated from the rms deviations between the LITA and the UPWT calibration values and are about 0.2% for Mach number, 0.4% for temperature and 4% for pressure. Uncertainties in the present pressure measurements are partly limited by the state-of-the-art knowledge of the absorption coefficient α in Eq. 2; improvements in knowledge of the low-temperature (100-300 K) behavior of α will reduce the present uncertainties. The LITA measurements of Mach number are absolute and need no normalization or calibration. The pressure and temperature comparisons were made by using a single point (near Mach 1.8) as a reference point (i.e., to measure x_o), and data at all other Mach conditions are measurements relative to this calibration.

In summary, barometry, thermometry, and velocimetry have been successfully performed simultaneously in a supersonic airflow. These three off-body flow measurements give an overall kinetic and thermodynamic characterization of the airflow, from one LITA instrument, at a spatially-resolved point. This novel demonstration of pressure determination illustrates a possible, noninvasive, and seedless alternative to the traditional intrusive Pitot probe. Potential applications include sonic boom reduction studies and computational fluid dynamics code validation.

We thank M. T. Fletcher for help with the LITA setup at the UPWT.

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Figure Captions

Fig. 1. Schematic of beam geometry near focal region of laser beams. In (a), two acoustic wave packets (vertical bold) are overlapped just after they are created at time t_o by the crossed pump beams (fine solid line). The probe and detector are omitted for clarity. In (b), the slower packet at Mach M-1 is shown passing through the probe beam (dash line) and scattering signal A_- at time t_-, after the faster packer at Mach M+1 has already scattered signal A_+ (arrowed dash) towards the detector at the Bragg scattering angle, at earlier time t_+.

Fig. 2. Comparison of LITA measurements and known UPWT flow parameters for time-averaged (a) Mach number, (b) temperature, and (c) pressure.
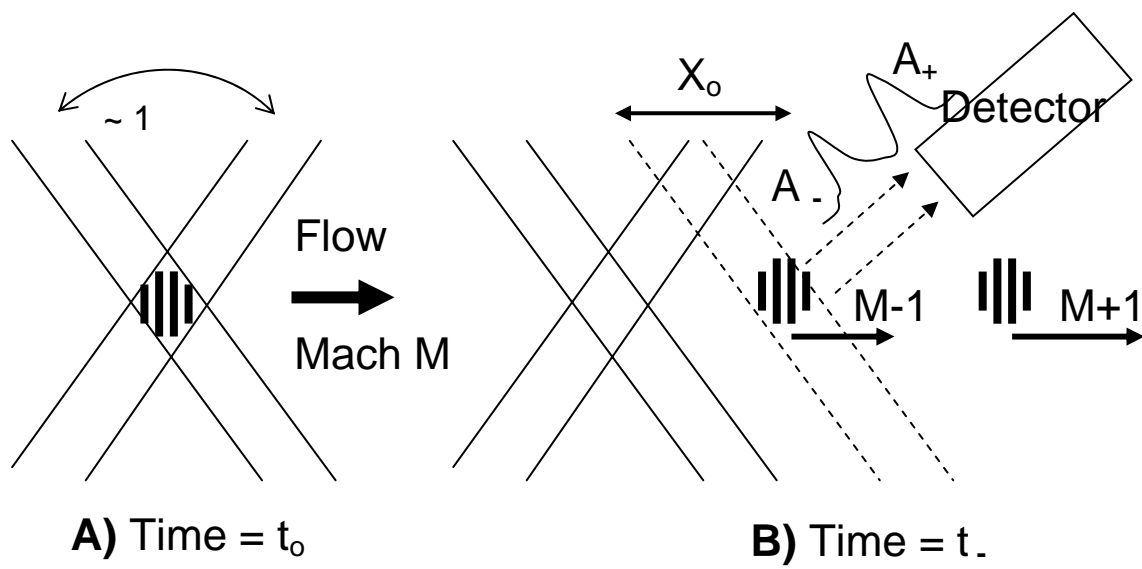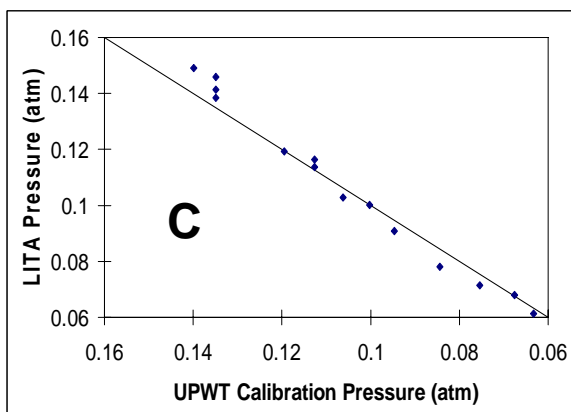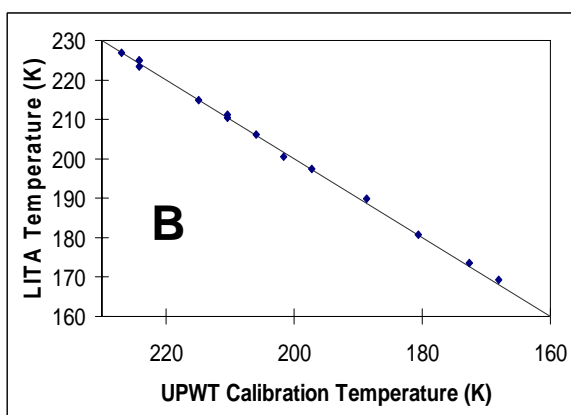
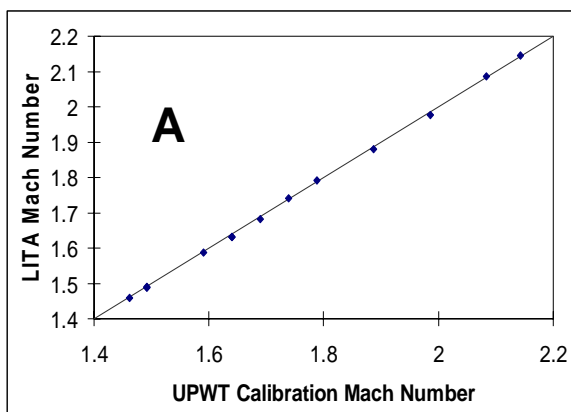**A)** Time = t_o

B) Time = t_-

Fig. 1

Fig. 2