Remote Acoustic Detection Using a Coherent Laser Radar

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Abstract: A coherent lidar was used to detect sound remotely in an unseeded wind tunnel. The system is able to reconstruct acoustic temporal waveforms by detecting the motion of natural aerosols. The acoustic motions were measured in the presence of much larger motions caused by the ambient fluid-dynamic turbulence. Unlike conventional microphones, remote acoustic sensing is immune to wind-induced self-noise and avoids disturbing the aerodynamic flow. By forming a virtual microphone array it is possible to make the lidar system directional, thereby rejecting acoustic reflections from wind tunnel walls. The system employs a continuous-wave, single-frequency, 1.55 µm fiber laser in a bistatic configuration and a heterodyne receiver with a 200 MHz intermediate frequency. The acoustic waveform was impulsive, characteristic of acoustic signatures of helicopters. There is close agreement between the lidar and conventional microphone signals.

Keywords: acoustics, virtual microphone, aerosol scattering, heterodyne detection

1. Introduction

There is longstanding interest in measuring the acoustic emissions of rotorcraft in flight [1], and in wind tunnels [2,3]. The logistical and empirical difficulties of previous methods that relied on conventional microphones are circumvented by a laser virtual microphone. A laser sensor mounted on an aircraft avoids the need to use another aircraft with a microphone flying in formation, as in ref. 1, or a ground array of microphones, which can only measure the acoustic field below the plane of the rotor.

2. Experiment

Figure 1 is a schematic diagram of the optical layout. The master oscillator is a continuous-wave, 125-mW fiber laser operating at 1.55 µm wavelength. The oscillator beam is sampled and shifted by 200 MHz by an acousto-optic modulator to form the local oscillator (LO). The remainder is amplified and focused at the probe volume. Light scattered from the aerosols is mixed with the local oscillator on the InGaAs photodetector with 1.5 GHz bandwidth. The bistatic arrangement restricts the probe volume of the sensor to a region much shorter than the acoustic wavelengths of interest. The crossing region of the transmitted and back-propagated LO beams defines a probe of 25 cm in length (FWHM) at a range of ~5 m. The lidar system measures the acoustic acceleration of aerosols by processing the Doppler spectrum of the scattered light.

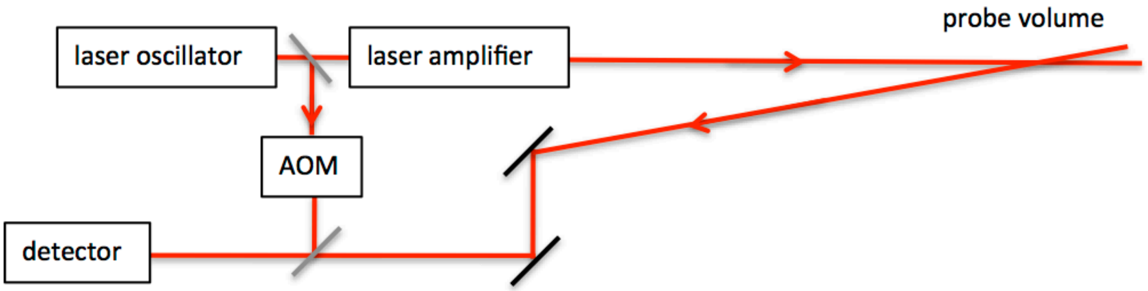


Figure 1. Optical schematic diagram.

The sensor was tested in Caltech's Lucas Wind Tunnel (Fig. 2). It is a closed-return tunnel capable of speeds up to 60 m/s with a 1.3 m x 1.8 m x 7.5 m test section. The nominal test section static pressure is 98.7 kPa. The sensor was assembled on an optical breadboard under the wind tunnel. The optical transmit/receive beams were introduced into the tunnel using a mirror attached to a steel crossbar bolted to the outer frame of the tunnel. The laser beam entered the tunnel in the gap between the test section and the tunnel return. Since the mirror was downstream of the test section it did not disturb the flow in the test section. A 15" speaker was installed in the wall of the test section.

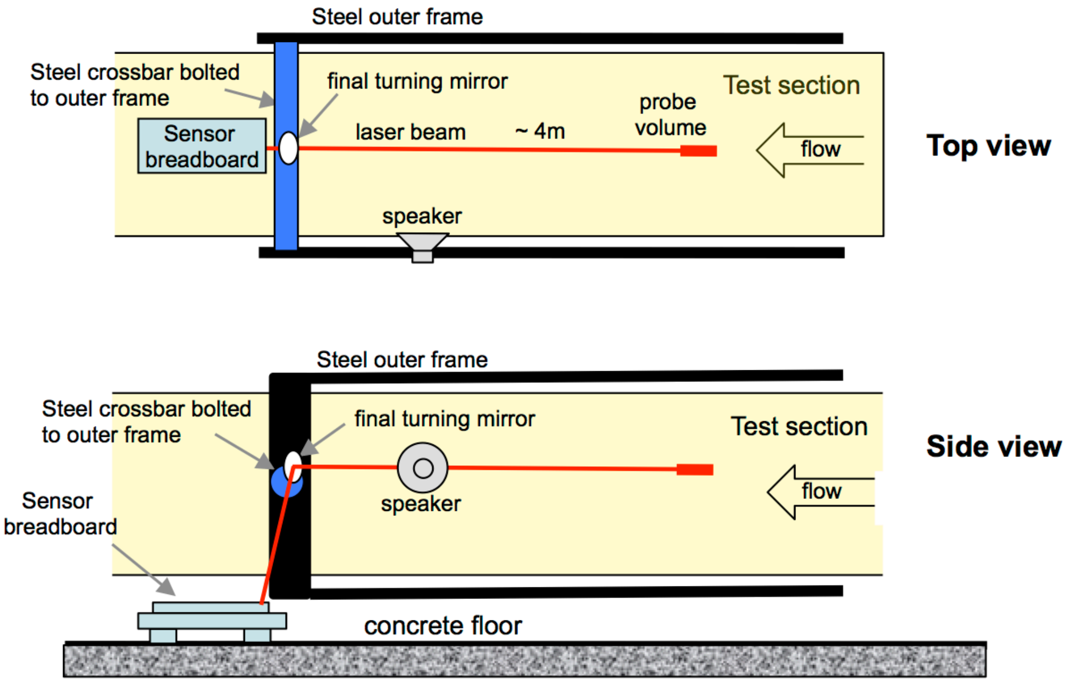


Figure 2. Schematic diagram of the installation of the sensor in the wind tunnel.

The cross section of the wind tunnel measures 1.3 x 1.8 m, which results in a reverberant environment, as the walls are not acoustically treated. Since the laser sensor measures acoustic motion *along* the beam direction, the microphone measurements must be configured to measure this motion to the exclusion of acoustic motions in other directions.

The pressure was measured with a B&K 2260 Investigator sound analyzer at two positions along the laser beam axis. Subtracting the two pressure time series and dividing by the microphone spacing results in an approximate measurement of the pressure gradient:

$$\frac{\partial p}{\partial x} \approx \frac{p_2 - p_1}{x_2 - x_1} \tag{1}$$

The acoustic motion along the laser beam axis is related to the gradient in pressure by Newton's law:

$$-\frac{\partial p}{\partial x} = \rho \frac{\partial u_x}{\partial t}, \tag{2}$$

where ρ is the density of air and u_x is the acoustic velocity component along the beam axis. The microphone pressure gradient was compared with the signal extracted by the laser, which is related to the particle acceleration.

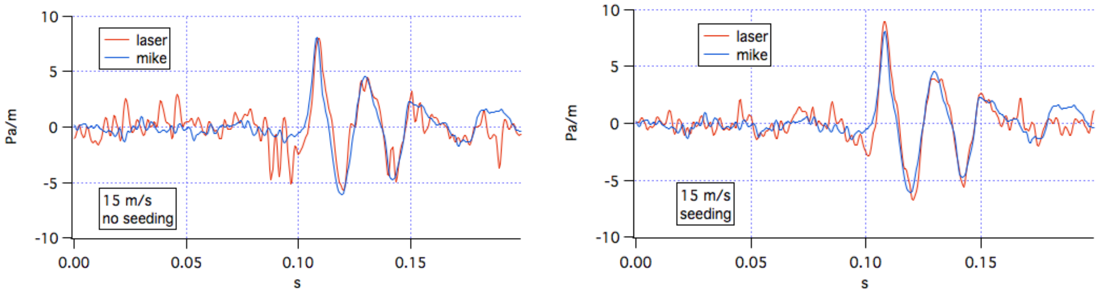
The laser sensor relies on scattering from ambient particles in the flow. Natural air normally contains sufficient numbers of particles to enable the sensor to extract signals with a limited amount of averaging. Since the Lucas Tunnel is closed, the concentration of particles is much lower than typical natural air. Consequently, averaging of the acoustic signals over many repetitions was required to obtain signals with acceptable signal-to-noise ratios. Light seeding of the tunnel with water droplets at densities comparable to clean outdoor values results in good signals with less averaging. The measured particle densities are tabulated below.

Table 1. Particle Densities

particle diameter (μm)	density (particles/cm^3)	
	no seeding	light seeding
0.7	0.18	0.80
1.0	0.10	0.28
2.0	0.045	0.035

Figure 3(a) shows a comparison of the laser and microphone signals without seeding, averaging 200 pulses at 15 m/s wind speed; Fig. 3(b) shows the comparable data with light seeding and only averaging 50 pulses. The pressure gradient measured by the microphone (Eqn. 1) is plotted as a function of time and compared with the pressure gradient calculated from the particle acceleration measured with the laser sensor (Eqn. 2).

Both laser signals agree well with the microphone: the correlation between laser signal and microphone signal is 0.84 in the unseeded case and 0.92 in the seeded case. There is more noise in the unseeded case, suggesting more averaging was required. The measurements were repeated at 25 m/s wind speed resulting in a correlation of 0.59 for both unseeded and seeded cases.



(a) no seeding (200 averages) (b) light seeding (50 averages)

Figure 3. Comparison of microphone and laser sensor signals.

In the far field of the source, the pressure time series can be computed from the time integral of particle acceleration since pressure is related to acoustic velocity by the following relation:

$$p(t) = \rho c u(t) = \rho c \int \frac{\partial u_x}{\partial t'} dt' \qquad (3)$$

3. Acknowledgements

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4. References

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