AEROSOL MICROPHYSICAL PARAMETER MEASUREMENTS BY AUTODYNE Nd^{3+}:YAG-LASER TRANSCEIVER

S.D. Burakov, A.P. Godlevskii and S.A. Ostanin

Special Design Bureau Scientific Instrument Manufacture "Optika" SB, USSR Academy of Sciences
and
Institute of Atmospheric Optics, SB, USSR Academy of Sciences
634055 Tomsk, USSR
Received November 21, 1988

An autodyne cw Nd^{3+}:YAG-laser Doppler anemometer was evaluated. The experimental results obtained are reported. The feasibility of remote sensing of aerosol microphysical parameters, such as aerosol particle velocity, acceleration, size, scattering cross-section, and number density, using the proposed system is shown.

Airborne particulate and aerosol velocity measurements are known to be efficient means of determining liquid-gas flow dynamic characteristics. The light particle velocity nearly equals the flow velocity whereas this is not the case with heavy species. For a particle size of $\lesssim 0.3$ μm, the velocity lag is $\lesssim 0.01\%$[1] up to a velocity pulsation frequency of 3 kHz. However, the detection of radiation scattered by a single aerosol particle of this size appears to present a great problem. Conventional laser Doppler anemometers used for this purpose provide only in situ measurements, have poor optical noise immunity, and require sophisticated high-accuracy optical systems.

In recent years, for weak reflected or scattered laser signal detection, wide use has been made of the autodyne reception technique[2,3] based on the dynamic response to the echo backscattered into the laser cavity, Zuev et al.[4,5], have reported a threshold CO_2-laser sensitivity of 10^{-13} W/Hz$^{1/2}$ to its backscattered echo.

Similar experiments have been carried out using a Nd^{3+}: YAG laser[6] to yield a return detection limit as low as 10^{-17} W/Hz$^{1/2}$, with the laser noise parameters approaching the quantum noise level. Lawrence et al.[7] evaluated a coherent CO_2-laser anemometer. Since the particle velocity was derived from the Doppler spectra for a particle ensemble, the motion pattern of single particles was not investigated. The infeasibility of simultaneous measurements of Doppler frequency and the scatterer size renders velocity estimates for radiation scattering by large particles in turbulent flows incorrect.

This paper reports on the results obtained from a study of an autodyne laser Doppler anemometer designed for remote sensing of the single aerosol particle velocity. Particle acceleration, size, number density and scattering cross-section measurements are presented. For the relatively low beat frequencies (as compared to CO_2 -laser tranceiver relaxation oscillations) encountered in the case of a slow target velocity, the laser output is modulated at the beat frequency[8]. In doing so, the modulation amplitude is given by

$$d_m = J_0 \beta g(g-1)$$

where J_0 is the steady-state photon density within the laser cavity, β is the return signal action coefficient, and g is the actual-to-threshold pump power ratio.

Consider a sounding scheme based on an autodyne solid-state laser transceiver operating in the visible or near-IR spectral region. In this case the Doppler shift w_m for any particle velocities found in the atmosphere satisfies the relation

$$w_m > w_r$$

where w_r is the laser relaxation oscillation frequency. For weak external signals such that $J(t) = I_0 + i(t)$, $i(t) \ll J_0$, and Doppler shift w_m, a set of self-consistent balance equations for the population inversion and photon number within the resonator in the low amplitude approximation results in the following variable component[8]:

$$i(t) = -i_m[\cos(\omega_m t + \varphi) - e^{1/2g\tau^{-1}} \cos(\omega' t + \varphi)],$$

$$\operatorname{tg}\varphi = w_m g\tau^{-1}/(w_m^2 - w_R^2),$$

$$w' = [w_R^2 - (g\tau^{-1})^{-2}/4\,]^{1/2}, \tag{1}$$

where τ is the laser level relaxation time, with

$$i_m = \frac{J_0 Q_0 \sigma \beta v \left[w_m^2 + (g\tau^{-1})^2\right]^{1/2}}{\left[(w_m^2 - w_R^2) + (w_m g\tau^{-1})^2\right]^{1/2}}$$

Here Q_0 is the cavity Q-factor, v is the velocity of light in the active medium.

It follows from Eq. (1) that at moderate pump levels $w' \approx w_R$. For echo returns from single aerosol particles passing through a focal region of the transmit-receive optics, the laser modulation occurs at two frequencies w_m and w_R. For $w_m \gg w_R$ the foregoing considerations lead to the relation

$$i_m = J_0 Q_0 \beta v \left[1+(g\tau^{-1})^2 \right]^{-1/2}$$

which indicates that the laser intensity response is linearly dependent on the return signal action coefficient β.

Since at relatively low velocities ($v/c \ll 1$) a dominant role is played by the longitudinal Doppler effect, it is possible to measure the velocity vector component parallel to the optical sounding axis.

Additionally, the scattering cross-section and particle size can be determined. For the single-particle scattering, the differential cross-section is linearly related to the variable component intensity:

$$I_m(t) = I_0(t) d\sigma R^{-2} d\Omega^{-1} \tag{2}$$

Here $d\Omega$ is the solid angle, R is the range from the scatterer, $I_0(t)$ is the Doppler signal variable component amplitude for the specular reflection in the backward direction. Equation (2) allows dσ to be readily estimated. For laser scattering by small species, the particle size and the differential scattering cross-section are correlated by the equation[1]

$$d\sigma = \frac{r}{k^2} \left[\frac{n-1}{n^2+2} \right] d\Omega \tag{3}$$

where k is the wave number, n is the aerosol refractive index, and r is the particle radius. Equation (3) yields the particle size. The measured time separation Δt between two Doppler signals gives the particle density $n = (\Delta \bar{t} \bar{v})^{-3}$ upon averaging over a great number of realizations.

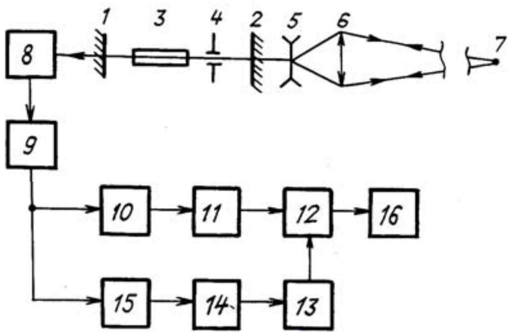

FIG. 1. Experimental setup: 1, 2 – laser cavity mirrors; 3 – Nd^{3+} YAG rod; 4 – diaphragm; 5, 6 – Galilean telescope; 7 – focal region; 8 – photodetector; 9 – amplifier; 10 – low-pass filter; 11 – rejection filter; 12 – A/D converter; 13 – clock-pulse generator; 14 – trigger; 15 – amplitude detector; 16 – PDP 11.

A schematic diagram of the experimental setup is shown in Figure 1. The Nd^{3+}: YAG-laser cavity is formed by a totally reflecting mirror and an output mirror 2 with a 40% transmission coefficient. A 5 mm diam×100 mm length Nd^{3+}:YAG crystal rod was used. The cw laser power was 20 W. The laser output was focused by a Galilean telescope 5, 6 at point 7. The distance from the focal point could be varied from 1 to 60 m. The measurements were made on a single particle within a focal range of 10 μm. A fraction of the aerosol-scattered radiation collected by the telescope was fed into the resonator. Lasing kinetics was monitored by an FD-256 silicon photodiode[8]. The photodetector signal was then amplified by the preamplifier. The high-frequency signal component was separated out by a low-pass filter[10] and entered a rejection filter[11] to be further suppressed at the relaxation oscillation frequency ω_R. Finally, the signal was digitized by an A/D converter. The latter was actuated by a clock-pulse generator[13] controlled by a Schmidt trigger[14]. The trigger opened the circuit when the amplitude detector[15] noise level exceeded that of the photodiode during pauses between particle fly-bys. A crate-controller connected the converter and a digital storage device to PDP-11[16] for signal analysis.

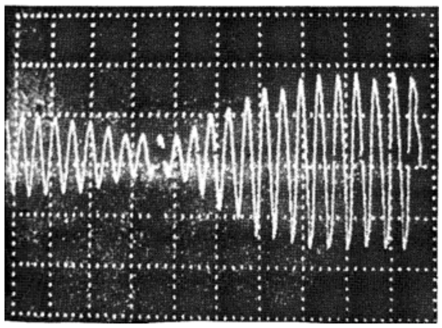

FIG. 2. Doppler signal oscilloscope trace

Figure 2 shows a Doppler signal scattered by a single aerosol particle. At high SNR's, a signal oscillation period was derived from the number of zero crossings for a given time. For signal amplitudes comparable with the noise amplitude, the oscillation period was determined from the autocorrelation function.

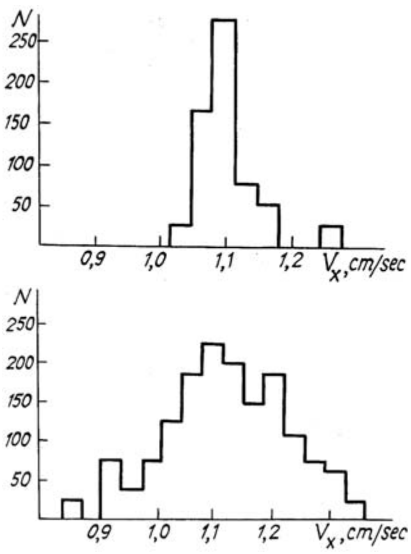

FIG. 3. a) Aerosol free-fall velocity distribution; b) The same as in (a) for convection conditions.

The analysis of the Doppler-shifted signal sequence yields the scatterer velocity distribution that in turn leads to such parameters as the most probable particle velocity, the mean velocity and the velocity variance. The latter allows an insight into the air flow movement behavior. Thus, for example, a narrow velocity distribution accounts for a laminar vector flow, whereas a distribution with no pronounced maximum suggests a flow turbulization.

Figure 3a shows an aerosol free-fall velocity distribution for a particle radius of 8 μm and a mean velocity of 1.1 cm/sec. According to Stokes' law the ultimate particle fall velocity in a viscous medium is estimated to be 0.7 cm/sec. The velocity distribution of Fig. 3b corresponds to free fall in a convection current.

In turbulent conditions the temporal behavior of the particle velocity exhibits an irregular pattern. Hence, the Doppler signal frequency will be a random function of time. Just as in the case of the accelerated motion of the target particle, the signal is frequency modulated to furnish the information on $v(t)$ and, consequently, $a(t)$ where a is the particle acceleration. In a strongly turbulized flow or one moving with a great acceleration, the particle velocity is appreciably changed at ranges on the order of the probed volume. Therefore, the carrier-to-shift frequency ratio during the particle transit time may be as high as $\gtrsim 2$, i.e. the particle has enough time to dramatically change its velocity within only 3–4 Doppler signal oscillation periods. At high frequency deviation rates (the relation $\frac{dw}{dt} \ll w^{z}$ is violated) the laser demodulation was effected by choosing the signal digitization rate to be much higher than the Doppler frequency. Note that each signal data sample of no more than three values corresponded to a signal at a fixed frequency:

$$w(t_j) = \sqrt{I(t_j)/I(t_j)}$$

where $\check{I}(t_j)$ is the second-order derivative of the signal at the z-th instant of time. Naturally, the function $w(t)$ thus obtained contains second-order derivative jumps at the signal inflection points. The spikes are fairly well eliminated by band-pass filters using a FAT algorithm or a recursive filter code.

The demodulation efficiency was verified by recording the return signal backscattered by water aerosol particles irradiated by an acoustic wave from a diffuser. In this case the travel of light particles corresponds to the diffuser displacement. The Doppler signal of the particle is shown in Fig. 4a, and the diffuser displacement rates and the results of demodulation of the Doppler signal are shown in Figs. 4b and c. A comparison of Figures 4b and c shows the proposed demodulation technique to provide encouraging results. The function $a(t)$ is determined by differentiation

$$a(t) = \frac{dv(t)}{dt}$$

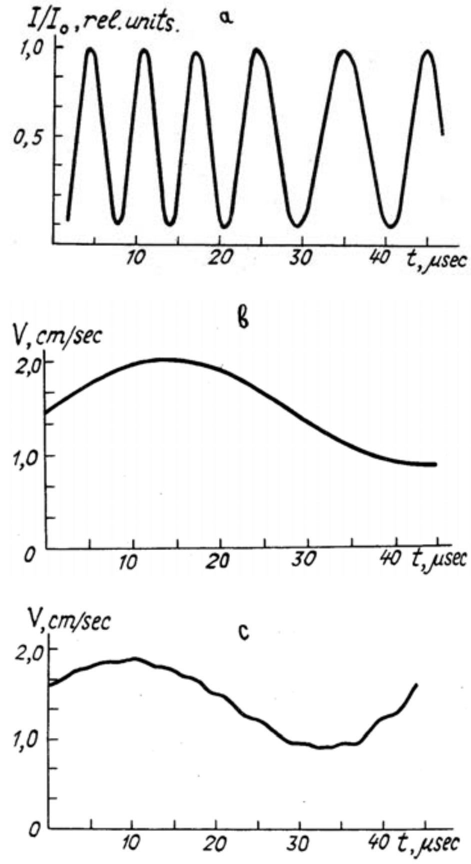

FIG. 4. a) Doppler signal from single aerosol target particle subject to acoustic wave; b) Diffuser displacement rate; c) Aerosol particle velocity profile vs. diffuser displacement rate.

Our autodyne Doppler anemometer measurement capabilities are summarized below. The maximum detectable aerosol density limited by the signal processing speed amounts to 1.5×10^{10} m^{-3}. A minimum detectable aerosol velocity of 36 μm/sec is determined by the laser noise spectral band whereas a maximum detectable aerosol velocity of 2 cm/sec is due to the A/D converter operating speed. The minimum total scattering cross-section of 1.2×10^{-10} μm^2 corresponds to a 1 μm-particle. The anemometer sounding range is 60 m. Thus, the experiments indicate the feasibility of remote measurements of aerosol microphysical parameters. The use of a stabilized laser supply source and a fast-response A/D converter would dramatically improve the performance of this type of anemometer.

In conclusion, it is to be pointed out that autodyne anemometers are very attractive tools for plasma and flame exploration owing to a high noise immunity of the system against background obtained in the coherent laser-reception of echo-signals.

REFERENCES

1. Yu.N. Dubnihschev and B.S. Rinkevichus *Laser Doppler Anemometry Techniques* (Nauka, Moscow, 1982)
2. E.P.Gordov, A.P.Godlevskii, Ya.Ya.Ponurovskii, et al., App. Opt. **26**, No. 9, 1607 (1987)
3. V.E. Zuev, A.P. Godlevskii, Yu.D. Kopytin, et al., Opt. Comm. **62**, No. 6, 370 (1987)
4. V.E. Zuev, S.D. Burakov, A.P. Godlevskii, et al, in: Abstracts of the XIIIth Int. Laser Radar Conf., Ottawa, 125 (1986)
5. V.E. Zuev, S.D. Burakov, A.P. Godlevskii, et al., in: Abstracts of the XIIIth Symp. of the IMEKO, Braunschweig, 49, (TC-2) (1987)
6. E.A. Viktorov, N.M. Galaktionov, A.A. Mak, et al., Opt. Spektrosk. **62**, 430 (1987)
7. T.R. Lawrence, D.J. Wilson, C.E. Craven, et al., Rev. Sci. Instrum. **43**, 512 (1972)
8. S.D. Burakov and Yu.D. Kopytin an: Abstracts of the VIIIth All-Union Symposium on Laser and Acoustic Sounding of the Atmosphere. Part II, 78, Tomsk, (1984)