Flow Tracing Fidelity of Scattering Aerosol in Laser Doppler Velocimetry

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Abstract

An experimental method for determination of the flow tracing fidelity of a scattering aerosol used in Laser Doppler Velocimeters was developed with particular reference to the subsonic turbulence measurements. The method employs the measurement of the dynamic response of a flow seeding aerosol excited by acoustic waves. The amplitude and frequency of excitation were controlled to simulate the corresponding values of fluid turbulence components. Experimental results are presented on the dynamic response of aerosols over the size range from 0.1 to 2.0 μm in diameter and over the frequency range 100 Hz to 100 kHz. It was observed that unit density spherical scatterers with diameters of 0.2 μm followed subsonic air turbulence frequency components up to 100 kHz with 98 percent fidelity.

I. Introduction

The application of a Laser Doppler Velocimeter (LDV) to the characterization of turbulence in subsonic and supersonic fluid flow is gaining broad acceptance.[1-4] Almost invariably, tracers are needed in the fluid medium

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to obtain Doppler shifted Mie scattered radiation for the fluid velocity measurements. The reliability of LDV measurements in a fluctuating fluid velocity field is dependent on the fidelity of the tracer particles to follow the fluid motion. The size, the concentration, and the physical characteristics of the scattering aerosol are of paramount importance in the application of a Laser Doppler Velocimeter to fluid turbulence measurements. In general, the upper size limit of the aerosol is determined by particle inertia, and the lower size limit is determined by the increasing Brownian motion and the molecular slip in addition to the decreasing light scattering cross-section as a result of decreasing particle size. In a transonic or supersonic flow field where the flow medium is seeded with a scattering aerosol for velocity measurement, a considerable velocity lag may exist between the fluid motion and the motion of the suspended particles. A polydisperse aerosol may cause an apparent spread in the measured velocity distribution since a wide spectrum of aerosol size would result in a wide distribution of particle velocity lags. Thus, the scattering aerosol should be fairly monodisperse in size. The particle concentration should be sufficiently low so as to produce a negligible perturbation of the flow field, yet the concentration should provide the necessary amount of data in order for meaningful results to be obtained within the time of measurement. The physical properties of the particles should be such that the aerosol is fairly stable, non-corrosive, non-toxic, and compatible with the physical properties of the fluid medium and the flow dynamics.

The theoretical aspects of the dynamic characteristics of the suspended particles in a fluid medium have been studied by several workers, notably by Chao,[5] Tchen[6] and Soo,[7] and the practical implications of their studies to LDV measurements in turbulent flow fields have been discussed in many recent reports.[8-12]

The technique presented in this paper provides a method for experimental determination of the dynamic response of the tracer particles. In this method, a known oscillatory fluid velocity field is generated by an acoustic excitation of the medium. The frequency response of the suspended particle is measured by LDV, and the results are compared with the fluid velocity amplitudes measured with a microphone. Experimental data on particle response in the frequency range of 100 Hz to 100 kHz are presented and the theoretical aspects are briefly reviewed. A set of criteria for the optimum choice of an aerosol for turbulent flow seeding is suggested, and a method for generation of a submicron aerosol for flow seeding is described.

II. Equation of Motion of a Small Suspended Particle in a Non-Stationary Fluid Medium

For a small free spherical rigid particle in a locally uniform flow field, the force balance can be written from Newton's second law

$$m_p(dV_p/dt) = F_D + F_e \tag{1}$$

where m_p is the mass of the particle, V_p is the particle velocity, F_D is the fluid resistance force, and F_e represents the summation of the forces acting on the particle other than the fluid resistance forces. Examples of the latter forces are the gravitational force, "buoyant" or "lift" forces caused by pressure gradients as well as by the presence of a shear layer of fluid, thermal forces, and electrostatic forces.[7,8]

The fluid resistance force F_D can be expressed as

$$F_D = C_D(1/2)\pi r_p^2 \bar{\rho}_g (U_g - V_p)|U_g - V_p| \tag{2}$$

where C_D is the drag coefficient, r_p is the particle radius, $\bar{\rho}_g$ is the average value of the fluid density, U_g is the vectorial velocity of the fluid, and V_p is the vectorial velocity of the particle. The drag coefficient, C_D, is a function of the particle Reynolds number, Re, which is given by

$$Re = d_p V_{pg} \bar{\rho}_g / \bar{\eta} \tag{3}$$

where $V_{pg} = |U_g - V_p|$,

d_p is the particle diameter, and $\bar{\rho}_g$ and $\bar{\eta}$ are the average values of density and viscosity of the fluid, respectively.

For small Reynolds numbers, Re < 1, where the inertial forces are small in comparison with the viscous forces in the medium, C_D can be represented by

$$C_D = 24/(ReC_c), \tag{4}$$

which indicates that the particle motion is in the Stokes' Law Regime. The term C_c represents the Cunningham Correction Factor[7] for the molecular slip.

If only one dimensional components of U_g and V_p are considered, and are denoted by u_g and v_p, the equation of motion of a small spherical particle in turbulent flow can be approximated in the following form:[6]

$$(dv_p/dt) + av_p = au_g + b(du_g/dt) + c\int_{t_0}^{t} \{(du_g/dt' - dv_p/dt')/(t - t')^{1/2}\}dt' \tag{5}$$

where $a = 36\bar{\eta}/\{(2\rho_p + \bar{\rho}_g)d_p^2\}$

$b = 3\bar{\rho}_g/(2\rho_p + \bar{\rho}_g)$

$c = 18(\bar{\rho}_g\bar{\eta}/\pi)^{1/2}/\{(2\rho_p + \bar{\rho}_g)d_p\}$

and ρ_p is the particle density. Tchen[6] solved this equation to obtain the ratio of the Lagrangian energy-spectrum function $E_p(\omega)$ for the particle to the Lagrangian energy-spectrum function for the fluid $E_g(\omega)$. The relationship can be expressed as

$$E_p(\omega)/E_g(\omega) = \{1 + f_1(\omega)\}^2 + f_2^2(\omega) \qquad (6)$$

where
$$f_1(\omega) = \frac{\omega(\omega + c\sqrt{\pi\omega/2})(b - 1)}{(a + c\sqrt{\pi\omega/2})^2 + (\omega + c\sqrt{\pi\omega/2})^2},$$

$$f_2(\omega) = \frac{\omega(a + c\sqrt{\pi\omega/2})(b - 1)}{(a + c\sqrt{\pi\omega/2})^2 + (\omega + c\sqrt{\pi\omega/2})^2},$$

ω, $2\pi f$, is the angular frequency of turbulence components, and the constants a, b, and c are defined above.

When the particle Reynolds number Re < 1, and $\rho_p >> \bar{\rho}_g$, the terms containing the constants b and c in Equation (5) can be neglected. Under these conditions Equation (6) can be simplified as follows

$$E_p(\omega)/E_g(\omega) = 1/(1 + \omega^2\tau_p^2). \qquad (7)$$

τ_p is the dynamic relaxation time[13] of the particle which can be expressed as

$$\tau_p = (1/a)C_c = \rho_p d_p^2 C_c/18\bar{\eta}. \tag{8}$$

The term C_c, the Cunningham Correction Factor, becomes significant when d_p is smaller than or comparable to λ_g, the molecular mean free path. The mean free path increases significantly as the flow approaches the free molecular regime in high mach number flows.

Equation (6) can be verified experimentally by subjecting the seed particles to a known sinusoidal fluid velocity field. The equation of motion of a particle of radius r_p in an oscillatory flow field can be written in the form[13]

$$\begin{aligned} m_p(dv_p/dt) = {} & -6\pi\bar{\eta}r_p(v_p - u_g) \\ & + 6\pi\bar{\eta}r_p(\omega r_p^2/2\bar{\nu})^{1/2}\Big[(u_g - v_p) + (1/\omega)d(u_g - v_p)/dt \\ & + (2/3\omega)(\omega r_p^2/2\bar{\nu})^{1/2}(du_g/dt)\Big] \end{aligned} \tag{9}$$

where ν is the kinematic viscosity of the gas and ω is the angular frequency of oscillation.

A possible method of generation of a known oscillatory fluid velocity flow field is the excitation of the fluid medium by an acoustic field. When the term containing $(\omega r_p^2/2\bar{\nu})^{1/2}$ in Equation (9) is small (less than 0.01), the motion of the particle is in Stokes' Law Regime. Under this condition, the motion of an oscillating particle in an acoustic field, can be written in the form

$$\tau_p(dv_p/dt) + v_p = u_g \sin \omega t. \tag{10}$$

Equation (10) represents one dimensional motion of a particle in an acoustic field of angular frequency ω. The steady state solution for the ratio of the amplitude of the particle velocity to the amplitude of the fluid velocity is given by

$$(v_p/u_g) = 1/(1 + \omega^2\tau_p{}^2)^{1/2}. \tag{11}$$

The ratio (v_p/u_g) is referred to as the degree of fidelity and is denoted by μ_p. The velocity amplitude of an element of fluid subjected to an acoustic plane wave of intensity I in watts/meter^2, is given by

$$u_g = (2I/\bar{\rho}_g c_g)^{1/2}, \tag{12}$$

where c_g is the velocity of the propagating acoustic wave.

Equation (11) indicates that the fidelity with which an aerosol particle follows the fluid motion increases with decreasing particle diameter, particle density and excitation frequency, and with increasing viscosity of the medium.

Motion of suspended particles in an oscillating fluid can be studied by subjecting the aerosol to an acoustic plane wave. Since the energy of turbulence in a fluid flow is distributed over a spectrum of frequencies, experiments carried out at discrete frequencies can be related to the motion of particles in a turbulent fluid if the fluid turbulence conditions are simulated.

III. Tracking Fidelity of Aerosol in a Turbulent Flow Field

From Equation (7), it is evident that the fidelity of an aerosol in tracing the fluctuating fluid motion cannot be 100 percent for particles with a finite value of τ_p. Thus a finite amount of velocity lag, however small, will always be present. The velocity lag decreases with decreasing particle size. However, the particles must also be efficient scatterers at the wavelength of the laser radiation and for a given incident power, and hence a compromise must be made on the particle size. In order to judiciously select tracer particles for LDV measurements, one must consider the desirable scattering properties, the acceptable minimum molecular slip, the practical considerations for aerosol generation, as well as the implications of Equations (5) and (9) for obtaining high flow tracking fidelity. Considering all of the above, the following set of constraints may be written to specify the tracer particles for subsonic air turbulence measurements:

$$\begin{aligned} \omega\tau_p &< 1.0 \qquad (13) \\ (\omega r_p^2/2\bar{\nu})^{1/2} &<< 1.0 \\ (\bar{\rho}_g/\rho_p) &<< 1.0 \\ Re &<< 1.0 \\ Kn &\leq 0.5 \\ \sigma_g &\leq 1.5 \\ (m_p n/\rho_g) &\leq 0.01. \end{aligned}$$

The above conditions are not mutually independent but do set criteria relating to the physically meaningful quantities. The first four criteria, which are derived from Equations (3), (5) and (9), imply that the flow is in the Stokes' Law Regime, and also that the dynamic relaxation time of the particle is small. These four constraints can be used to specify an upper limit of the particle size for a desired value of (v_p/u_g). The last three constraints which specify (1) a lower limit of the particle size, (2) the aerosol size distribution, and (3) aerosol number concentration n, respectively, are based on reasonable assumptions. The fourth constraint, $Re << 1.0$, is satisfied in most actual subsonic flow cases, as will be shown later, where $d_p \leq 1.0$ μm, $\rho_p = 1.0$ gram/cc and the frequency of turbulence does not exceed 100 kHz. The requirement that the Knudsen number $(Kn = \lambda_g/d_p)$ be equal to or smaller than 0.5 implies that the molecular slip is small. This condition also satisfies the requirement for the particles to be effective scattering centers at visible wavelengths. The sixth condition implies that the seeded aerosol should be fairly monodisperse and that the geometric standard deviation (σ_g) of the particle size spectrum should be close to one. Because of inherent difficulties in generating a truly monodisperse aerosol and because of the unstable nature of aerosols, a maximum value of 1.5 is chosen as a practical limit for σ_g. A larger value of σ_g may cause appreciable error in turbulence measurement because of the possible wide distribution of particle velocity lags. The last constraint implies that the particulate mass loading ratio be small; thus perturbation of the flow field will be negligible and coagulation[13] of the aerosol will be small. The lower limit of particulate concentration in the flow medium is set by the Doppler signal "dropouts." The maximum percentage of Doppler signal dropout that can be tolerated in a LDV system depends on the turbulence parameters being measured, available time for measurements and on the method of Doppler signal demodulation. In general, the photon correlation technique requires a minimum concentration of tracer particles; the digital counter technique (which measures the time of flight of particles as each particle crosses the sensing volume) requires a relatively higher particulate concentration; and the analog frequency tracker method is effective when the data acquisition is quasi-continuous requiring a particulate concentration of the order of 10^5 particles/cc or higher.

Figure 1 shows the calculated values of the desired aerosol size spectrum if unit density spherical tracer particles are to be used for the measurement of turbulence. The line designating particle inertia limit is calculated for tracer particles with 98 percent flow tracing fidelity (v_p/u_g = 0.98) in the flow field of a known turbulence frequency spectrum. The minimum value of the particle diameter is indicated by the vertical line for Kn = 0.5 for air at STP. The suggested minimum diameter is thus 0.12 μm. Also plotted in Figure 1 is the approximate nature of variation of the normalized scattering cross-section[14,15] (K_s), as a function of particle diameter assuming that the aerosol is fairly monodisperse with refractive index m = 1.33, and the wavelength of incident radiation is 488.0 nm. It is observed that when Kn $\leq$ 0.5, K_s is greater than 10^{-2}, a reasonable value for moderate incident laser power. As an illustrative example, if fluid spectral density in a turbulent fluid flow is to be measured up to a frequency of 100 kHz, the diameter of flow tracing particles should be in the limit $0.12 \leq d_p \leq 0.25$ μm, for ρ_p = 1.0 gram/cc. It is assumed that the particles are uncharged, inert and not volatile in the surrounding fluid.

In setting up the above criteria, a linear particle-fluid interaction was assumed. In most actual turbulent flow cases, temperature, density and dynamic viscosity of the fluid are variables and the fluid resistance force becomes nonlinear. Additional nonlinear behavior of the particle motion may arise because of the particle shape factors (for non-spherical particles), or because of thermal and electrostatic forces. Since nonlinear couplings are involved, the particle response is a function not only of excitation frequency, but also of the particle Reynolds number and particle relaxation time. Thus the validity of Stokes Law must be verified in a given experimental situation or in a simulated velocity field. If acoustic excitation is employed for simulation, the dynamic components of the acoustic accelerating force applied to the particle should correspond to the components of the fluid accelerating force that a particle will actually experience in the flow field to be investigated by using a Laser Doppler Velocimeter.

Figure 2 illustrates typical values of experimentally obtained[7] root mean square turbulence velocity components as a function of frequency of turbulence in a subsonic wind tunnel. The unbroken line represents the isotropic turbulent velocity components in a 25 cm-diameter wind tunnel with a mean air velocity of approximately 300 meters per second. The curves shown in broken lines represent corresponding calculated rms Reynolds numbers of a spherical, unit density, one μm-diameter particle suspended in the fluid medium. Thus the particle Reynolds number Re is much smaller than 1 for unit density submicron particles suspended in a turbulent flow field.

The fidelity of seeded particles in tracking the fluid velocity fluctuations in a subsonic turbulent flow field can be experimentally determined by measuring the ratio of the particle velocity amplitude to the fluid velocity amplitude while the particles are in an oscillatory flow field of comparable velocity amplitude at the frequency of excitation. Earlier experimental studies[16] on the particle motion in a sonic field were rather indirect since an estimation of particle velocity was made by photographically recording the amplitude of vibration of the aerosol in a limited amplitude and frequency range. The experimental technique employed in the present studies measures realtime particle velocity. The technique may be used to measure amplitude and spectral components of particle velocity in a wide range of frequency and intensity levels of acoustic excitations.

IV. Experiments

An experimental arrangement for measuring the frequency response of a scattering aerosol is shown in Figure 3. A 500 mW argon-ion laser beam of wavelength 488.0 nm is incident on the outermost track of an optical encoder disc having a spatial frequency of 100 lines/mm. The disc is rotated at a sufficient speed by a synchronous motor to permit a 2 MHz translation[17] in the frequency of the Doppler signal. The test aerosol is suspended in an acoustic excitation chamber. Air at room temperature was used as the fluid medium. The fluid medium containing the test aerosol was excited by acoustic radiators. The frequency of excitation could be varied at discrete steps from 100 Hz to 100 kHz. The Doppler signal was demodulated by a phase-locked loop demodulator using a Signetics NE 561B PLL circuit. The acoustic pressure levels at the point of velocity measurements were measured by using a 0.635 cm diameter, Type 4135 calibrated Bruel and Kjaer condenser microphone followed by a B&K Model 2618 preamplifier.

Acoustic excitation in the frequency range below 15 kHz was carried out using loud speakers including tweeters, Galton whistles, and acoustic fluid relaxation oscillators. Sound pressure levels in the range of 100 to

140 dB were used at different resonant frequencies of the chamber. For the transmission of ultrasonic vibrations into the fluid medium, flexural vibrating plates were used. A typical transducer driven by a piezoelectric crystal is also shown in Figure 3. The transducer consists of a circular, flexurally vibrating, free-edge plate with stepped thicknesses. The plate is driven at its center and it can vibrate at several resonant frequencies corresponding to different flexural modes of vibration. A number of ultrasonic radiators were made with different resonant frequencies. The output acoustic levels in air 3 cm from the ultrasonic radiators could be varied from 100 dB to 145 dB in the frequency range 20 to 100 kHz. In terms of fluid velocity amplitudes (u_g) the amplitude of oscillation can be varied from 0.5 cm/sec to 120.0 cm/sec. The acoustic excitation used, simulated the velocity oscillation of the fluid medium containing a test aerosol to represent turbulent velocity components in magnitude and frequency as shown in Figure 2. The maximum particle Reynolds number realized in the present set of experiments was 0.01. The experiment duplicates the turbulence velocity components. However, the length scale of the fluctuating field is effectively infinite whereas in an actual turbulent flow field the length scale is small.

Three types of aerosol generators were used to generate test aerosols for particle response studies. Laskin atomizers[4,10] were used to generate polydisperse DOP aerosols (ρ_p = 0.98 gram/cc, refractive index m = 1.4 at λ = 500.0 nm, σ_g = 2.23, MMD = 0.8 μm, n ≈ 10^7 particles/cc). A Rapaport-Weinstock generator[14,18] was used to generate fairly monodisperse DOP aerosol (σ_g = 1.3, n ≈ 10^5 particles/cc) in the size range 0.1 to 1.5 μm in diameter. These two generators produce liquid droplets and are well described in the literature.

A third type of generator was used to generate aerosols of monodisperse solid particles. Monodisperse aerosols containing solid spherical particles were generated by atomizing an alcohol suspension of Dow polystyrene latex spheres (ρ_p = 1.05 grams/cc, m = 1.58 at λ = 500.0 nm). Uniform polystyrene latex particles in the size range 0.1 to 2.0 μm and with a standard deviation of 0.005 μm were used. The aerosol generator is shown in Figure 4. A lucite tube, 0.64 cm I.D. and 1.27 cm O.D., with 6 radial holes of 0.33 mm diameter was used as an atomizer. The bottom end of the tube was closed. The open end was connected to a pressurized N_2 tank through a pressure regulator and an absolute filter. The radial holes were positioned so that the nitrogen gas jets skim the surface of the suspension. A dilute suspension was used to produce an aerosol in which most of the latex particles were singlets. It was found that the latex particles in an alcohol suspension have less tendency to coagulate when the solution concentration is altered. Also, the alcohol film on the particles evaporates faster than the water film which is present if water suspension is used. The particulate concentration can be varied from 10^2 to 10^5 particles/cc.

The method of determining the particle response in an oscillatory fluid velocity field was as follows: The test aerosol was introduced into the acoustic excitation chamber by connecting the input of the chamber to the aerosol generator while the other port of the chamber was connected to a vacuum line. After a suitable concentration of aerosol was obtained inside the chamber, both ports were closed. The acoustic exciter was then energized and the acoustic pressure level at a point close to the laser beam crossing was measured by the microphone. The velocity oscillations of the aerosol were measured by the Laser Doppler Velocimeter. Both the modulating signal (microphone output) and the demodulated signal (Doppler signal processor output) were displayed on a dual beam oscilloscope. Velocity amplitudes u_g and v_p were calculated from the oscilloscope displays. A sample of aerosol was taken from the chamber and its photomicrograph was analyzed to determine the aerosol size distribution. The process was repeated for each test aerosol. Figure 5(a) shows a typical oscilloscope display of the modulating signals and the demodulated signals for two particle sizes and for an acoustic excitation of 37.6 kHz. The waveform with the larger amplitude represents particle motion of a 0.176 μm diameter polystyrene particle and the waveform with smaller amplitude was recorded for a 2.02 μm diameter particle. Figure 5(b) shows the response of a polydisperse DOP aerosol in the same acoustic field. These displays show clearly the velocity and phase lags of the test aerosols in an oscillating fluid when particle inertia becomes significant.

Acoustic excitation levels at the point of velocity measurement were maintained at a constant level for a given frequency of excitation. The particle velocity amplitudes for different size particles can thus be directly compared from the oscilloscope display of the demodulated signal. Table 1 shows the ratio of the measured particle velocity amplitude for the test areosol to the measured particle velocity amplitude for particles of 0.176 μm-diameter polystyrene latex spheres. The choice of 0.176 μm-diameter particles as a reference for u_g was made since these particles were expected to follow an oscillatory flow field without any appreciable velocity lag in the frequency range DC to 100 kHz. For example, from Equation 11, $v_p/u_g = 0.994$ for f = 84.0 kHz. The relative amplitude ratio $(v_p/v_{0.176})$ was preferred to the ratio of v_p/u_g, since the measurement of u_g from the microphone output may have the following sources of error: (1) the microphone is not directional and thus it cannot measure the one dimensional component u_g alone if other orthogonal components are present, and (2) the size of the microphone becomes comparable to the wavelength of acoustic radiation at the higher frequencies. Figure 6 shows a plot of the theoretically calculated ratio of relative particle velocity amplitudes. Experimental data points show a close fit to the expected values.

The above experimental data proves the validity of Stokes' Law approximation to the fluid-particle interaction in a subsonic air turbulence for the test aerosols described above. If a homogeneous aerosol containing polystyrene latex particles is used to seed the flow field, the particle size to be used can be determined from Figure 1. If the turbulence frequency spectrum given in Figure 2 is to be measured by LDV, the optimum choice for the mean aerosol diameter would probably be 0.20 μm considering the desired light scattering cross-section and the fidelity of flow tracing. In a similar fashion, flow tracing fidelity of the other test aerosols can be determined if the flow characteristics are predictable.

In general, a monodisperse submicron aerosol of solid particles or of liquid droplets in the size range 0.1 to 0.3 μm satisfies the tracer particle requirements in subsonic turbulence studies by LDV. Liquid droplets of low vapor pressure have an advantage over the solid particles in that their deposition on the optical windows results in the formation of a liquid film that does not cause a severe light scattering problem from the window surfaces. Since an aerosol coagulates spontaneously, the coagulated liquid droplets remain spherical. However, solid particles with a high melting point are to be used where temperatures of the fluid medium are high. In many LDV applications to fluid flow studies, naturally occurring aerosol in the flow medium is used. In such cases, the physical characteristic of the aerosol must be determined to ascertain whether or not the particles satisfy the tracer particle requirements.

Equations (5) and (6) give a Lagrangian description of a particle motion in which the coordinate system is assumed to be moving with the mean velocity of the fluid. In practice, LDV measurements are made with fixed coordinate systems; thus, all measured turbulence data are Eulerian. The relation between Lagrangian and Eulerian spectral density functions for application to actual gas flow measurements is not fully understood. However, earlier studies[5,7] suggest that the measured Eulerian spectra can be correlated to the Langrangian spectra in many cases of practical interest, particularly when the particle size is very small compared with the turbulent eddies. The data presented here were taken in a Eulerian system, which actually represents the worst case. However, the data satisfy the Lagrangian description [Equations (5) through (7)] since, in the present experimental setup, the mean velocity of the fluid is zero and the particle is confined to the well-correlated region of fluid velocity fluctuations.

The experimental technique described in this paper also provides a novel method of testing the LDV system, particulary in determining the optical alignment, the signal-to-noise ratio, and the performance of signal processing techniques. Recently, considerable work[11] has been reported in the development of Doppler signal processing devices. Many of these signal processing units work satisfactorily when tested with an FM signal generated by an electronic signal generator yet fail to operate in a real LDV system. Since each LDV fluid flow application has different system requirements, the acoustic excitation technique generating a fluid velocity fluctuation may serve as a general-purpose tool for LDV performance studies.

V. Conclusion

The equation of motion for unit density spherical particles with diameters in the range from 0.1 to 2.0 μm in an oscillating fluid with a frequency in the range DC to 100 kHz is found to agree, within experimental errors, with Stokes' Drag Law of fluid-particle interaction for a particle Reynolds number less than 0.01.

An analysis ot the particle-fluid interaction and the scattering properties of the aerosol indicates that a fairly monodisperse aerosol of 0.2 μm mean diameter is the optimum choice for tracer particles in subsonic air turbulence studies employing a Laser Doppler Velocimeter. Experimental results on the acoustic excitation method presented here confirm this analysis. Methods of generating submicron aerosols for flow seeding of inert gases at ambient temperatures are discussed. The acoustic excitation method can also be used as a valuable tool in studying the performance of a Laser Doppler Velocimeter system.

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TABLE 1

Correlation of Theoretically Calculated and Experimentally Observed Velocity Amplitude Ratios (Note: $v_{0.176}/u_g$ = 0.994 @ 84 kHz)

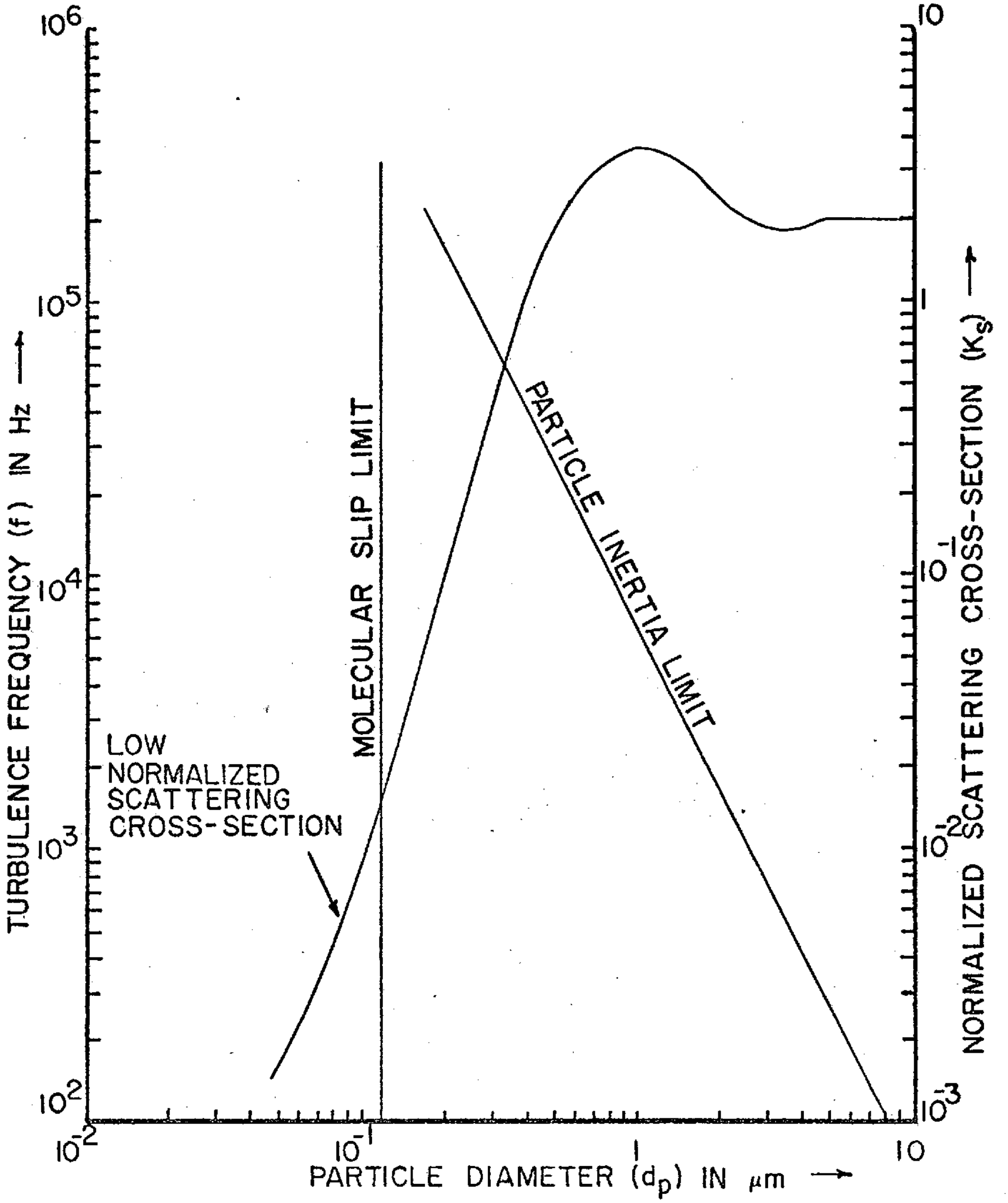
Frequency of Oscillation kHz	Particle Diameter in μm	$v_p/v_{0.176}$ Experimental	$v_p/v_{0.176}$ Theoretically Calculated (From Stokes' Law)
4.99	0.500	1.00	0.99
4.99	0.760	1.00	0.99
4.99	1.011	1.00	0.99
4.99	2.020	0.88	0.91
20.84	0.500	1.00	0.99
20.84	0.760	0.97	0.96
20.84	1.011	0.92	0.89
20.84	2.020	0.43	0.48
32.15	0.500	1.00	0.98
32.15	0.760	0.90	0.92
32.15	1.011	0.79	0.80
32.15	2.020	0.32	0.33
51.46	0.500	0.90	0.95
51.46	0.760	0.73	0.82
51.46	1.011	0.60	0.64
51.46	2.020	0.19	0.21
84.80	0.500	0.82	0.88
84.80	0.760	0.66	0.65
84.80	1.011	0.45	0.45
84.80	2.020	0.13	0.13

FIGURE CAPTIONS

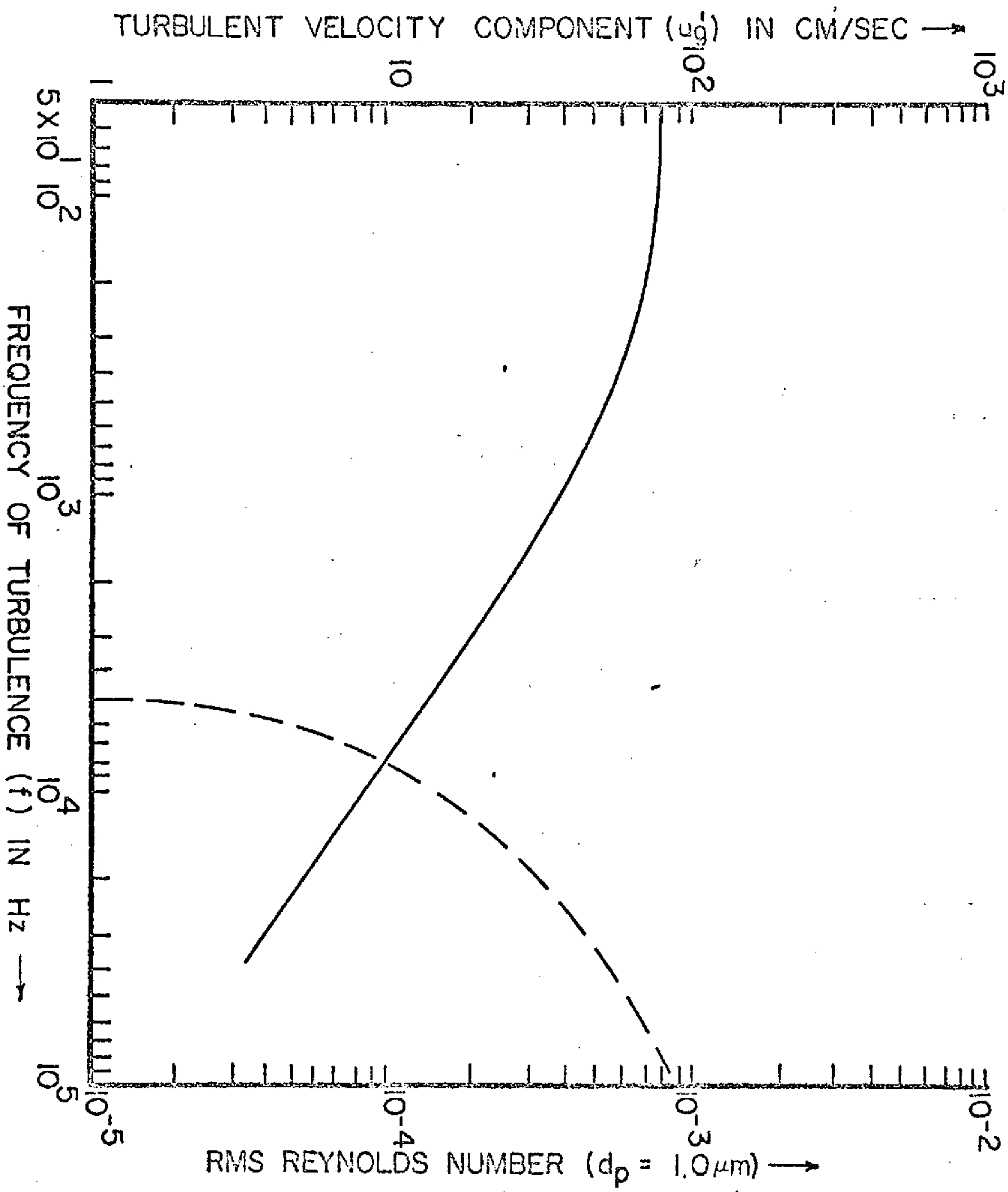
Figure Numbers	Caption
1.	The limit of unit density spherical tracer particle diameters as a function of the maximum value of turbulence frequency. The inertia limit is set by $(v_p/u_g) = 0.98$ and the molecular slip limit is set by $Kn = 0.5$. The normalized scattering cross-section is indicated as a function of the particle diameter.
2.	Experimentally obtained (Ref. 7) rms turbulent velocity components ($U_0 = 300$ m/sec) and the calculated rms Reynolds number of a unit density 1.0 μm diameter particle suspended in the fluid medium plotted as functions of turbulence frequency.
3.	An experimental arrangement for measuring the dynamic response of tracer particles in an acoustic field.
4.	Polystyrene latex particle aerosol generator.
5.	Typical oscilloscope displays of the waveforms of acoustic excitation and particle motion. (a) The top waveform represents the microphone output at 37.6 kHz. For the two waveforms at the bottom, the larger amplitude represents the motion of a 0.176 μm diameter polystyrene latex

particle and the small amplitude waveform represents motion of a 2.02 μm diameter polystyrene latex particle. (b) The top waveform represents the microphone output at 37.6 kHz and the bottom waveforms represent motion of polydisperse DOP aerosol.

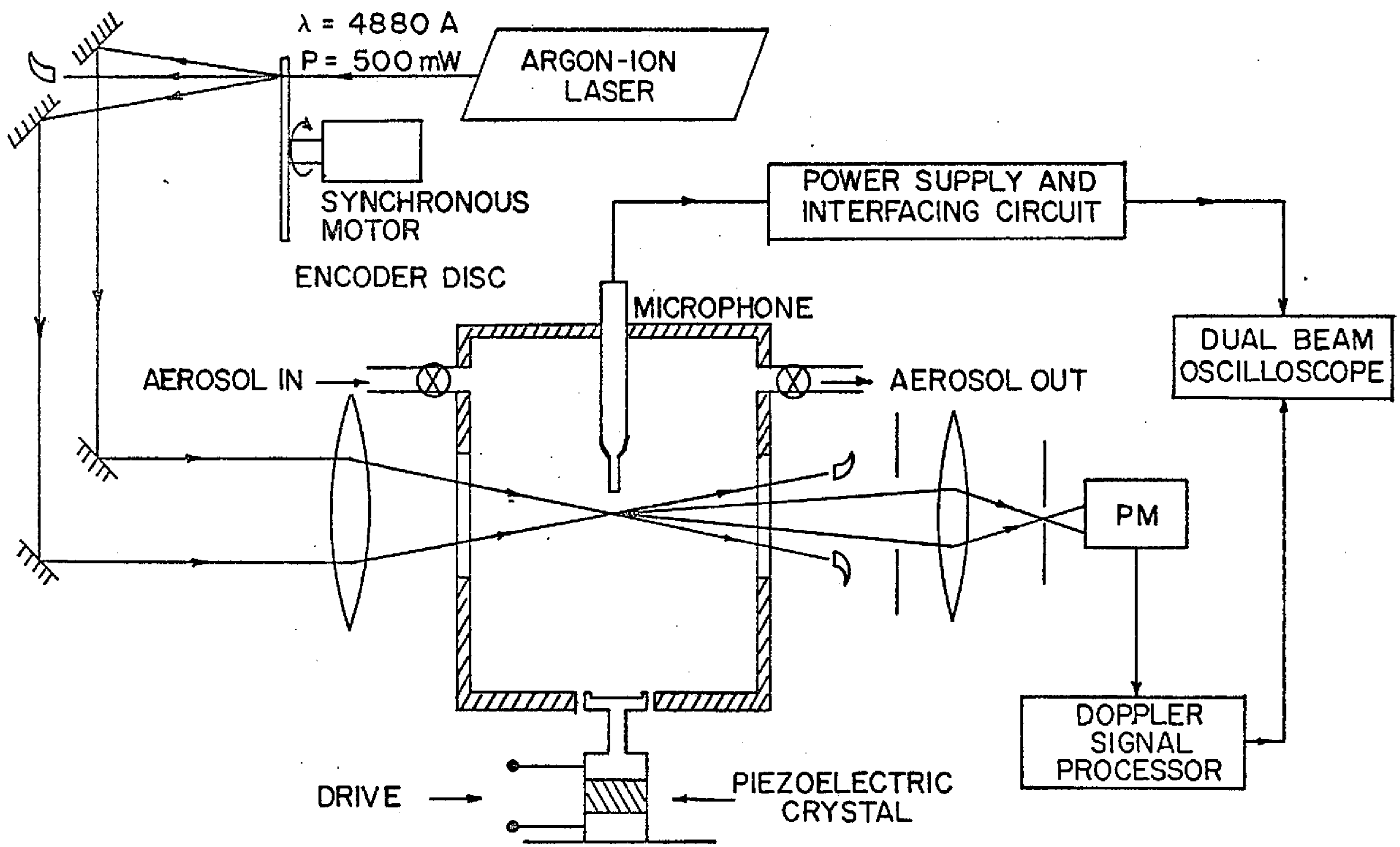
6. The velocity amplitude ratio for monodisperse polystyrene latex particles is calculated from Stokes Law and compared with the experimental data in the size range of 0.176 to 2.02 μm diameter and for the frequency range of 5 to 85 kHz.

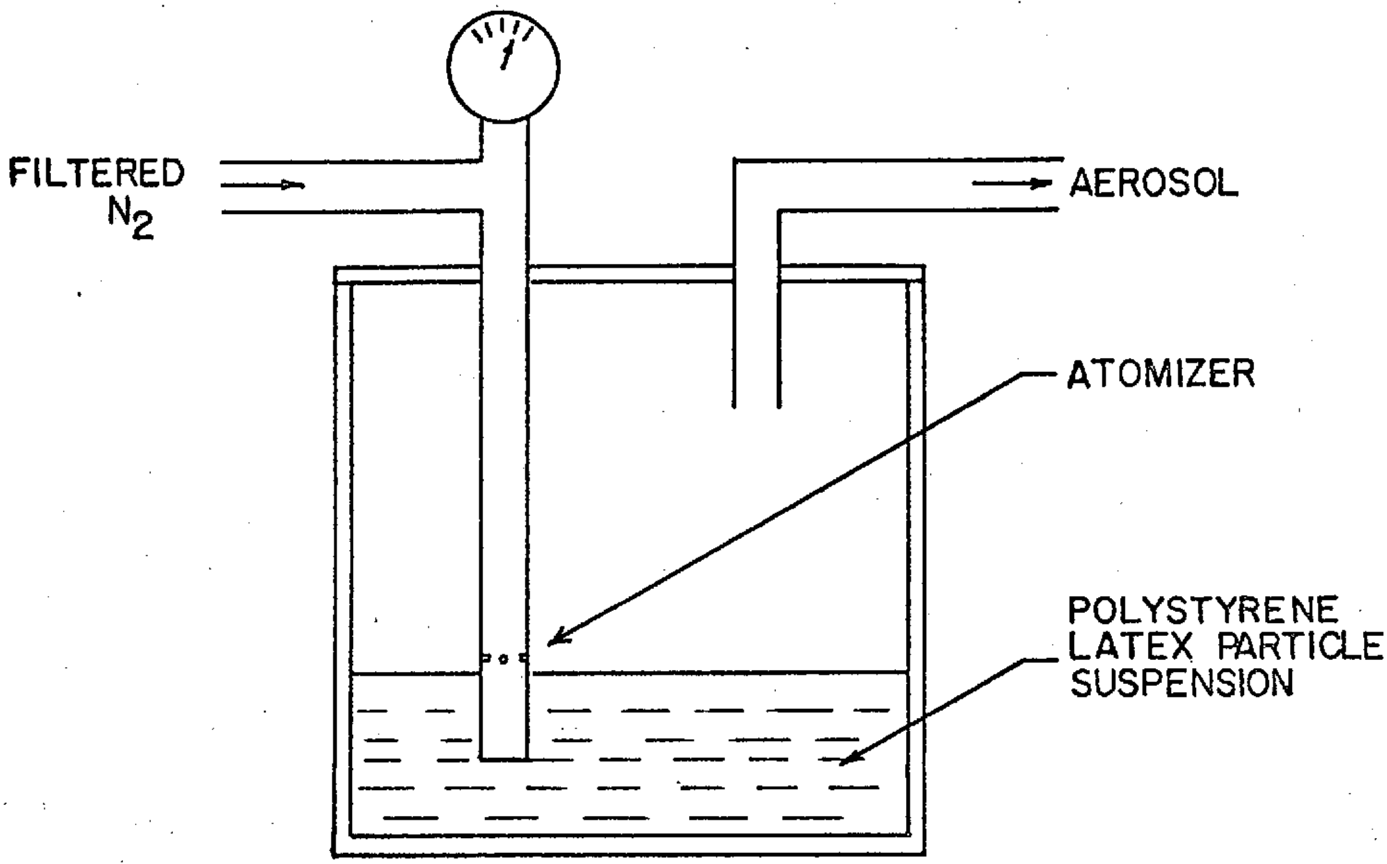


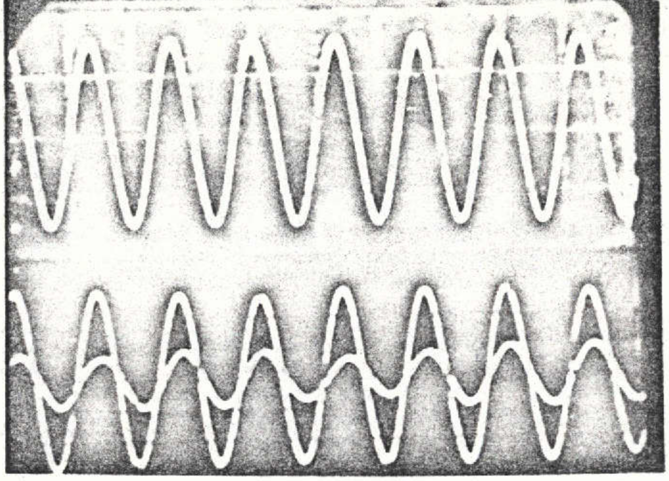
TURBULENCE FREQUENCY (f) IN Hz
NORMALIZED SCATTERING CROSS-SECTION (Ks)
PARTICLE DIAMETER (dp) IN μm
MOLECULAR SLIP LIMIT
PARTICLE INERTIA LIMIT
LOW NORMALIZED SCATTERING CROSS-SECTION



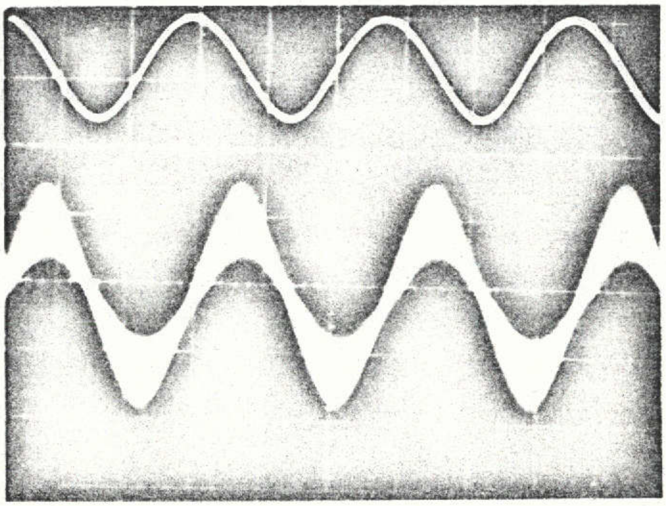
TURBULENT VELOCITY COMPONENT (u_g) IN CM/SEC →
1
10
10^2
10^3
5×10^1
10^2
10^3
10^4
10^5
FREQUENCY OF TURBULENCE (f) IN Hz →
10^{-5}
10^{-4}
10^{-3}
10^{-2}
RMS REYNOLDS NUMBER (d_p = 1.0 μm) →


λ = 4880 A
P = 500 mW
ARGON-ION LASER
SYNCHRONOUS MOTOR
ENCODER DISC
POWER SUPPLY AND INTERFACING CIRCUIT
MICROPHONE
DUAL BEAM OSCILLOSCOPE
AEROSOL IN
AEROSOL OUT
PM
DOPPLER SIGNAL PROCESSOR
DRIVE
PIEZOELECTRIC CRYSTAL

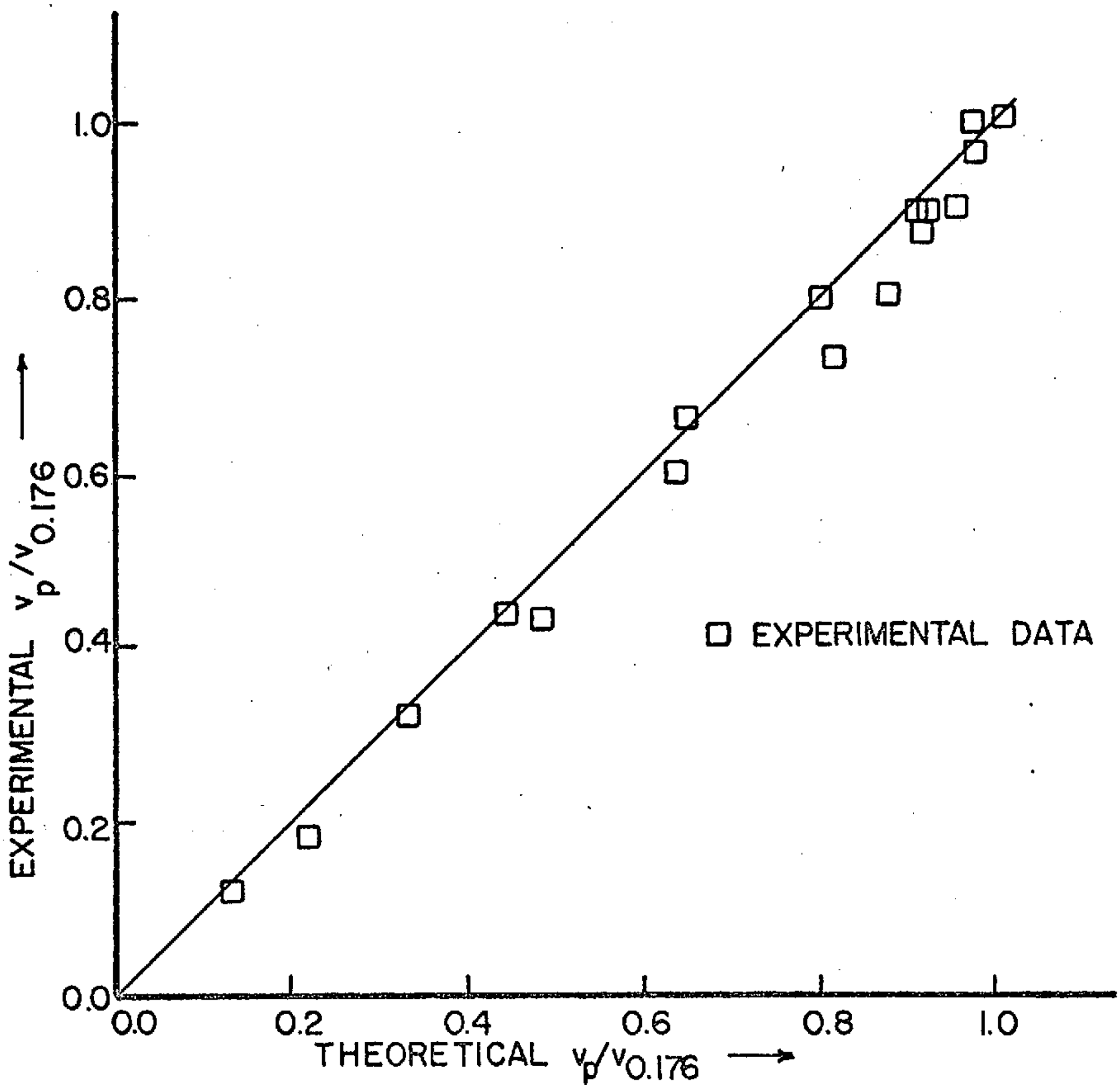

FILTERED
N_2
AEROSOL
ATOMIZER
POLYSTYRENE
LATEX PARTICLE
SUSPENSION



(a)



(b)



1.0
0.8
0.6
0.4
0.2
0.0
EXPERIMENTAL $v_p/v_{0.176}$
0.0
0.2
0.4
0.6
0.8
1.0
THEORETICAL $v_p/v_{0.176}$
EXPERIMENTAL DATA