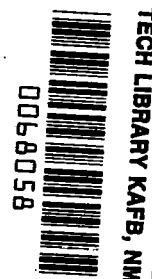# Development of a Simplified Optical Technique for the Simultaneous Measurement of Particle Size Distribution and Velocity

James Lee Smith

Development of a Simplified Optical Technique for the Simultaneous Measurement of Particle Size Distribution and Velocity

James Lee Smith
George C. Marshall Space Flight Center
Marshall Space Flight Center, Alabama

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF TABLES

NOMENCLATURE

Å	Angstroms
D	diameter
D_p	particle diameter
I	intensity
I_{max}	maximum intensity
I_{min}	minimum intensity
J_1	Bessel's function of the first degree
L,l	particle diameter
LDA	laser Doppler anemometry
PM	photomultiplier tube
R	radius from the center of the wheel to the laser spot
r_p	particle radius
RPM	revolutions per minute
V	velocity
X	fringe width
ΔX	fringe width
f	frequency
η	visibility
λ	wavelength
ΔXp	peak fringe width
N_r	fringes per meter
ℓ	mean particle diameter
σ	standard deviation

TECHNICAL PAPER

DEVELOPMENT OF A SIMPLIFIED OPTICAL TECHNIQUE FOR THE SIMULTANEOUS MEASUREMENT OF PARTICLE SIZE DISTRIBUTION AND VELOCITY

I. INTRODUCTION

Particle sizing devices and velocity measuring devices are presently limited to single or very finite particle counts. These devices are costly, bulky, and impractical. They are limited to highly specific applications and environments. Current techniques require complicated electronic frequency counters and other signal processing equipment.

The purpose of this project was to develop a simplified low cost optical technique for measuring particle size distributions and velocities simultaneously in gas streams. The specific application was measurement of heterogeneous reaction rates in fluidized bed gasifiers and combustors.

The objectives of Phase One of this project are as follows:

1) Survey existing techniques.

2) Develop experimental procedure for control cases.

3) Fabricate laboratory test model.

4) Recover limited data for proof of principle.

5) Illustrate relationship between particle size distributions and amplitude measurements.

The optical technique used for this project was a simplified version of the "dual-beam" laser-Doppler anemometer. In the standard "dual-beam" technique, split laser beams of equal intensity are intersected to produce sequential bright and dark fringes. The fringe pattern is produced with the equipment used for this project by simply interrupting a beam of light with Ronchi rulings (gratings). Physical interference is produced with the gratings as opposed to electromagnetic interference in the "dual-beam" method. The grating method is simple, portable, and low cost. An actual "Doppler-shift" does not occur, but it is mimicked by the variability of particle distributions between fringes.

II. LITERATURE SURVEY

A. General

Laser anemometry and particle sizing is a relatively new technological field with pioneer work beginning less than 20 years ago. The basis for laser Doppler anemometry (LDA) is scattered light interference, first recorded by Sir Isaac Newton in his "Optiks" (1704), and the "Doppler Effect," formulated by Doppler in the early 1800's.

When light is scattered off a moving surface a frequency shift called the "Doppler Effect" occurs. When the scattered light waves are beat together a precise velocity measure can be made using the beat (average) frequency. The following formula gives the velocity of the moving particle or surface:

$$V(velocity) = f(frequency) \cdot \Delta X(fringe\ width) \quad . \quad [1]$$

With the advent of lasers in the 1960's, LDA devices became feasible because a light source was now available that was collimated, monochromatic, coherent and of high intensity (Table 1) [2].

TABLE 1. COMPARISON OF LASER AND WHITE LIGHT

Laser	White
Collimated	Omnidirectional, disperses quickly
Monochromatic, constant frequency	Polychromatic, multiple frequencies
Coherent, in phase	Incoherent, out of phase
High intensity	Low intensity

In LDA a laser beam is split before or during inter-reaction with a particle or particles to produce fringes of light and darkness. There are three methods of LDA (to be discussed later). All three depend upon interference and scattering of light. Interference is the addition of two or more electromagnetic waves, constructively (to produce a more intense wave), or destructively (to produce a weaker wave or even anni-hilation of waves). In the LDA fringe pattern, constructive interference produces light bands and destructive interference produces dark bands. When a particle passes through a dark line, no light is scattered. When a particle passes through a bright line, light is scattered away from the particle. The intensity or "strength" of scattering depends upon particle size and type. A photodetector such as a PM tube can receive the scattered light and convert it to an electrical signal. The signal can, in turn, be processed electronically. (Signal analysis will be discussed later.)

B. Fluid Mechanics Applications

Standard mean velocity measuring devices for fluids include pitot-static tubes, hot-wire and hot-film probes, and eddy-shedding devices. All of these require insertion into the flow [1]. As a result, the flow is disturbed and inaccuracy occurs. Also, particulates in the flow can disrupt accuracy in measuring flow in fluids.

LDA devices do not disturb the flow, and they even take advantage of particulates in the flow. The only requirement of LDA devices is a light path into and out of the flow. An added advantage is that the particulates may also be sized. Also, toxic and corrosive liquids and gases that do not allow in-flow devices are open to LDA measurement.

2

Other important applications are furnaces, fluidic devices, gas and steam turbines, and engines where velocity and particle distribution are important.

The first application to fluid mechanics was described by Yeh and Cummins [3]. Their work was on laminar pipe flow.

C. Optical Arrangements

The three most common optical arrangements in LDA are the "reference-beam," the "dual-beam," and the "two scattered-beam" arrangements.

In the "reference-beam" method, the laser beam is split into an intense scattering beam and a weaker reference beam. Then the two beams are intersected to form a sampling volume. A photodetector receives a combination of the reference beam and the scattering beam which has been altered by particles passing through the "sampling volume." Figure 1 illustrates the "reference-beam" method.
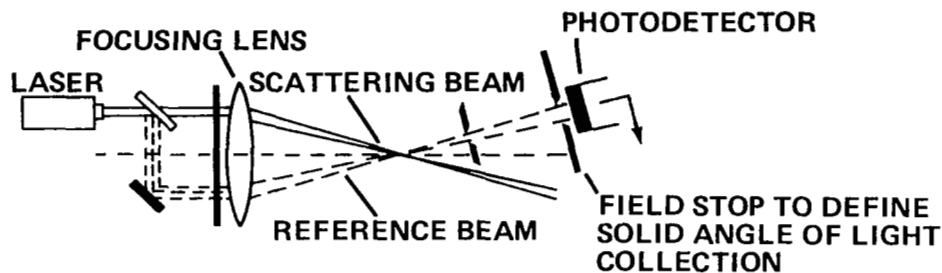

Figure 1. Reference beam system.

The "reference-beam" method was first used by Yeh and Cummings [3] to study laminar pipe flow. Since then it has been used by Goldstein and Hagen [4]; Welch and Tomme [5]; and Pike, Jackson, Bourke, and Page [6] in turbulent water flow applications. Lewis, Foreman, Watson, and Thornton [7]; Huffaker, Fuller, and Lawrence [8] all applied the same system to turbulent air flow. In 1971 Denison, Stevenson, and Fox used a variation of this method for laminar oscillatory water flow measurements [9]. Also in 1971 Goldstein and Kreid [10] did blood flow investigations utilizing the "reference-beam" method; Anderson, Edlund, and Vanzant [11] did LDA of shock waves in water; and Jackson and Paul [12,13] did supersonic flow experimentation. In 1977 Lee and Srinivasan [14] used "reference-beam" LDA for measuring local number density and velocity probability density for a dilute fluid system. Only single particles were measured. Both turbulent and laminar flow cases were considered. All of the "reference-beam" applications, with one exception, measured velocity only.

The "dual-beam" method consists of split beams of equal intensity intersected to produce interference fringes within the volume of intersection. The angle of intersection determines the width of the fringes. As particles pass through the fringes, the intensity of scattered light upon the photodetector rises and falls. This depends upon the size and number of particles, and is also directly proportional to the velocity of the flow. Figure 2 illustrates the "dual-beam" method.

Durst and Whitelaw [15] used this method to measure mean and fluctuating velocities in channel flow of water and in air jets.

In 1972 Rudd [16] investigated drag reduction by polymer addition; Lennert, Trolinger, and Smith [17] investigated vortices shed from aircraft wings; and vom Stein and Pfeifer [18] measured velocity

3

relaxation of micron-sized particles in shock waves. That same year Blake and Jesperson [19] callibrated impact probes for air jets. Durst, Melling, and Whitelaw [20,21,22,23]; and Durao, Durst, and Whitelaw [24] applied "dual-beams" to combustion systems. Farmer [25] measured particle size, number density, and velocity of single particles in 1972. When the fringe spacing is comparable to the particle's diameter, the size of the particle can be estimated; when the fringe spacing is much greater than the particle's diameter, the number density can be measured.
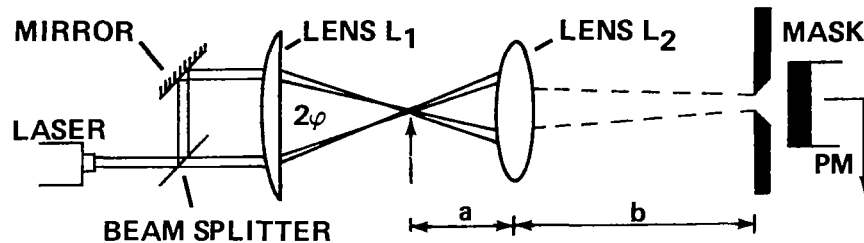

Figure 2. Dual beam system.

Baker, Bourke, and Whitelaw [26,27] did further work with combustion systems to determine velocity and particle size. Yanta [28] measured aerosols in wind tunnels using an LDA system that measured particle velocity lag of individual particles to determine particle size. Riethmuller and Ginoux [29] used "dual-beams" to size and measure velocity of particles in pneumatic tubes at 2 to 100 m/sec velocity and particle size range of 100 to 500 microns diameter.

In 1974 Farmer [30] continued his work of 1972 by sizing particles in the diameter range of 10 to 120 microns.

Wigley measured time averaged mean and fluctuating velocities in the gas flow of an oil-fired furnace [31].

In 1977 Roberds [32] sized single moving water droplets; and Birchenough and Mason [33,34] did velocity measurements of gas-solid mixtures. The gas was air and the solid was tobacco.

Oertel [35] measured density changes in fluids by "dual-beams" utilizing intensity measurements. In separate experiments, Unget, Yule, Taylor, and Chigier [36,37] measured single particle sizes of glass beads in a fluidized bed, and the concentration of particles in fuel sprays. Wigley [31] sized single water droplets between 1/10 and 1 mm.

Cline and Crosswy [38] reported on work at the Arnold Engineering Development Center. Most of the research was done in the area of velocity measurements of particles in wind tunnels. Some single particle sizing work was also conducted.

Birchenough, Mason, and Andrews [39] measured the velocity of 500 micron glass spheres in a 42 mm outside diameter pipe. The velocity range was from 3 to 25 m/sec. No report of sizing multiple particles simultaneously in "dual-beam" LDA was located.

The "two scattered-beam" arrangement consists of a single laser beam focused into the test volume. Scattered light is collected from two directions. Then the two scattered light beams are focused onto a photodetector. This method allows simultaneous measurement of perpendicular velocity components. The diagram, Figure 3, illustrates the "two scattered-beam" arrangement [1].
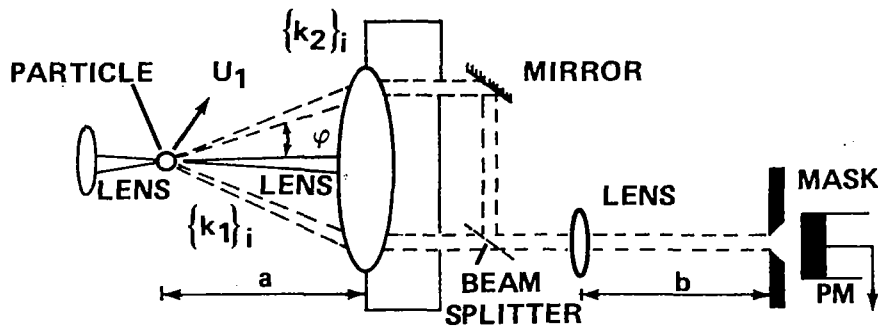
4

Figure 3. Two-scattered beam system.

In 1968 Fridman, Huffaker, and Kinnard [40] used a "three scattered-beam" arrangement. It was the same as the "two scattered-beam" method, but with three collection points as opposed to two. This arrangement was used to measure three-dimensional velocities.

Mazumder and Wankum [41], Durst and Whitelaw [42], and Mazumder [43] all did limited velocity research with the "two scattered-beam" method. No significant progress was made.

Wang and Snyder [44] and Lading and Hanson [45] did comparative studies of the three methods.

All three methods can use forward-scattering or back-scattering of light. No distinctions in signal quality are noted between the two scattering arrangements. However, certain situations do prohibit forward-scattering. Examples are dense gases and solid surfaces. Forward-scattering and back-scattering are illustrated in Figures 4 and 5.
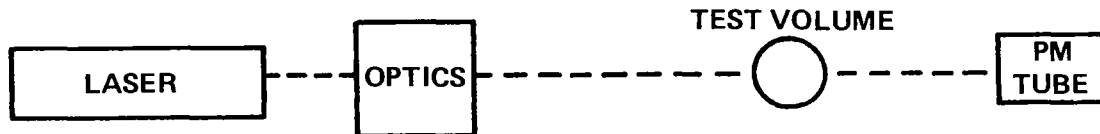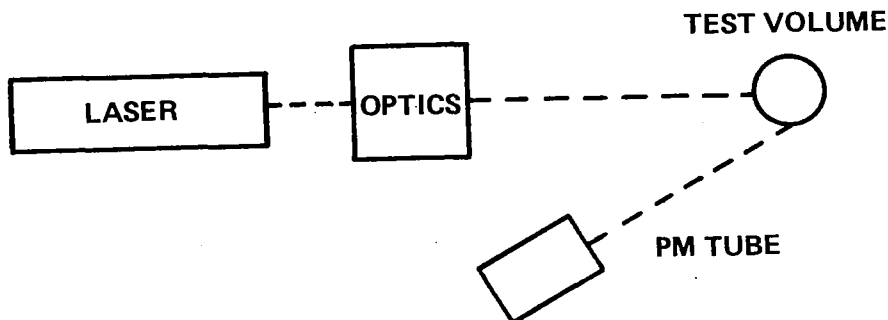

Figure 4. Forward scattering.

Figure 5. Back scattering.

D. Signal Processing

The first signal measurements were made with spectrum analyzers by which a probability density distribution can be processed. A long observation period is required. Using the mean frequency from the spectrum analyzer one can calculate mean velocity. There are usually many noise frequencies in the spectrum which must be avoided in interpretation of the signal [1]. The papers of Adrian and Goldstein [46] and Asalor [47] contain interpretation material for spectrum analyzer data.

Frequency trackers were later used because of their convenience. Also they require less time to collect data. Various versions have been developed by Fridman, Huffaker, and Kinnard [40]; Deighton and Sayle [48]; Iten and Mastner [49]; Mazumder [43]; Fingerson [50]; Smith-Saville [51]; and Wilmhurst and Rizzo [52]. Applications of the above are described in Huffaker [53]; Durst and Whitelaw [1]; Baker, Bourke, and Whitelaw [27]; Bourke, Drain, and Brown [54]; Durst, Melling, and Whitelaw [22]; and Durao, Durst, and Whitelaw [24].

Particles may be sized from photodetector signals. Intensity is a function of time, area of particle, and light source strength. If the velocity (time) and light source are constant, then intensity is a function of the particle cross-sectional area only. Visibility of the signal is a function of intensity only. From the Mie theory, visibility (η) is defined as follows:

$$\eta = \frac{2J_1(2\pi r_p/\Delta X)}{2\pi r_p/\Delta X} \tag{1}$$

In equation (1), J_1 is the first order Bessel's Function of degree one, r_p is the radius of the particle, and ΔX is the fringe width [1]. Farmer [25,55] used visibility to size single particles. This procedure is based on the Mie Scattering Theory, therefore, it only holds true for spheres [56]. Calculations of the visibility for scattered particles were made by Durst and Eliasson [57] in 1975.

In 1908 Mie obtained, on the basis of electromagnetic theory, a solution of the diffraction of a plane monochromatic wave by a sphere of any diameter. Mie's solution applies to multiple particles only if they are of the same diameter and composition, and if they are randomly distributed such that the distance between particles is large compared to the wavelength of light. This solution is Mie's Scattering Theory.

The experimental work for this report is based upon the same optical principles mentioned in the literature survey. The optical arrangement used in this report is a somewhat modified version of the "dual-beam" method.

III. DESCRIPTION OF EQUIPMENT

The optical arrangements discussed in the literature are sensitive to alignment. To measure different sizes of particles, one must change the angle of intersection of the laser beams. Too much time is required to measure a finite set of data where a wide range of particle sizes are present. The optical arrangement used for the experimental portion of this thesis utilizes Ronchi rulings which may be changed or rotated rapidly to vary the fringe spacing.

The equipment used to obtain data for this thesis is illustrated in Figure 6. The apparatus consisted of an optical bench on which lenses, light sources, and other equipment could be attached. A Spectra-Physics No. 124 helium-neon laser and its power supply is mounted on one end of the bench. The laser emits 10 mW of light in the visible range.
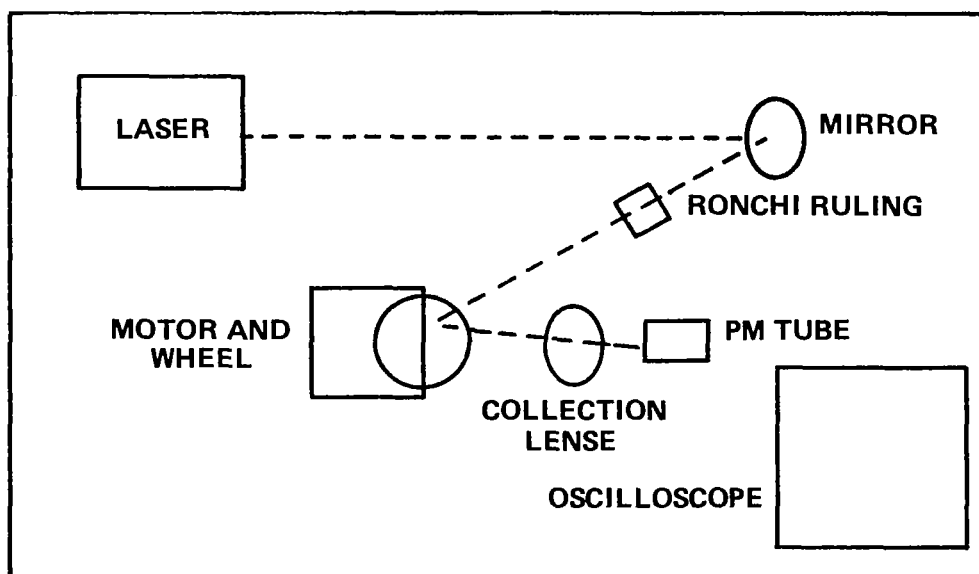

Figure 6. Diagram of equipment.

A flat mirror is mounted on the opposite end of the bench. The laser bench is reflected toward the center of the bench where the test surface is located. The Ronchi rulings are mounted between the mirror and the test surface.

The Ronchi rulings are from Fisher Scientific. The following sizes were used: 10, 25, 50, 100, 150, 200, and 300 lines per inch.

The test surface consisted of a flat steel wheel made from sheet metal. A shaft was attached to the wheel and in turn a motor. A variable speed laboratory motor with a built-in rpm gauge was used. The test specimens, sandpaper and glass beads, were attached to the wheel. Three types of sandpaper (coarse, fine, and superfine) were used. The origin of the glass beads is unknown. However, they were nearly perfect spheres with a narrow range of diameters.

A lens is located in front of the test surface to focus the scattered light on the PM tube. An RCA No. 8645 photomultiplier (PM) tube and an 1800 V power supply are mounted behind the lens.

A Tektronix oscilloscope is connected to the PM tube. A standard Polaroid oscilloscope camera is used to obtain photographs of the oscilloscope screen.

All distances, angles, and voltage settings remained constant so that none of these factors would have to be considered when processing the signal.

Although Ronchi rulings with fixed positions were used for this experiment, one can also rotate the Ronchi rulings to vary the number of lines per inch projected into the sampling space.

IV. EXPERIMENTAL PROCEDURE

A. Data Collection

All electronic equipment was allowed to warm-up for 10 min before initiating data collection. All voltage settings were constant for the entire procedure. The angle of intersection did not vary. The following distances were carefully calibrated and they remained constant throughout the experiment:

1) Laser to mirror

2) Mirror to Ronchi ruling

3) Ronchi ruling to test surface

4) Test surface to collection lens

5) Collection lens to photomultiplier tube.

The motor turning the test wheel was calibrated using the RPM counter. The distance from the center of the wheel to the laser "spot" was kept as nearly constant as possible to insure a near constant particle velocity. All data were taken at night to avoid interference from extraneous light and to prevent saturation of the photomultiplier tube.

The oscilloscope camera was loaded with Polaroid film and attached to the oscilloscope. The photographic procedure was as follows:

1) Open the shutter

2) Trigger the oscilloscope

3) Close the shutter

4) Remove the photograph

5) Number the photograph

6) Record data about the photograph.

One photograph was taken at a particular oscilloscope time setting. The time setting was changed and another photograph was taken. The photographic procedure was repeated for a large range of time settings so that complete cycles as well as individual peaks would be recorded. If a photograph of poor quality was taken, an additional one was taken at the same setting.

After completing a range of time settings, the Ronchi ruling was changed, and the procedure was repeated.

After the entire set of Ronchi rulings was used, the procedure was repeated for another velocity. 160 and 869 rpm were used to obtain the velocities for this experiment.

After recording data for all the Ronchi rulings at each velocity, the test medium (sandpaper or glass beads) was changed and the entire process was repeated.

B. Hand Count of Particles to Verify Results

An Olympus projection microscope was used to size particles for comparison. One hundred particles were sized at random for each grade of sandpaper. Since the glass beads approached perfect spheres of constant size, only ten of these were sized at random.

The particles were magnified on a projection screen where the diameters were measured by a standard ruler. The measurements were recorded. For odd-shaped particles the largest diameter was measured. The particle diameter was divided by the appropriate magnification factor to yield the effective particle diameter. Graphs of particle sizes and the associated statistics are indicated in Section V. Least-squares curve fit information is also shown.

V. DISCUSSION OF RESULTS

A. Particle Size Distribution Measurements

Since the purpose of this project was to develop the equipment and experimental procedures for proof of principle, a limited amount of data were recovered and processed. Sufficient data will be obtained during the second phase to develop the correlations and the theory required to measure particle size distributions.

The data retrieved for proof of principle are presented below. The test samples were disks with known particle size distributions. The disks were attached to a motor and rotated through the fringe pattern at constant angular velocity. A narrow particle size distribution was obtained by gluing beads to a circular disk. The distribution function for this case is indicated with Figure 7. Three different grades of sandpaper were used for the other test samples. The particle size distributions for these cases were obtained by counting and recording the number of particles in different size ranges. These distributions are indicated with Figures 8 through 10. The distribution characteristics for a best normal distribution "fit" to the data are indicated in Table 2. The variation of the light intensity produced by the progression of the particles through the fringe pattern was converted to an electrical signal with an RCA photomultiplier tube (No. 8645). This signal was displayed on the screen of an oscilloscope and recorded by photographing the same. The signal frequency did not exceed 5 kilocycles/sec. The frequency response of the photomultiplier tube and the oscilloscope were both in excess of 50 megacycles/sec, so there was no significant degradation of the signal. Examples of prints obtained for several signals are indicated in Figures 11 through 14. The fringes were obtained by projecting gratings with 10 to 300 lines/in. onto the test sample (sandpaper). There are two significant differences between the system used to obtain the data presented herein and prior work. First, the fringes are obtained by projection rather than by interference, so the system does not depend on a coherent, monochromatic and collimated source. Second, the variation of light intensity is a function of the variation of the samples of the particle size distributions between fringes rather than the simple scatter-no scatter (amplitude modulation) condition produced by single particle transit through the fringes. The amplitude of the velocity signal is, therefore, a function of the probability that the distribution will be significantly different between fringes at any given time. This, in turn, is a function of particle size, packing (number of particles per unit volume), fringe width, index of refraction, and velocity.

The amplitude of the velocity signal was plotted as a function of fringe width. This data is indicated with Figures 15 through 18. The data were reduced to dimensionless form by dividing the amplitude by its maximum value and the fringe width by the value of the fringe width at which the maximum amplitude occurs (ΔX_p). This simple procedure grouped the data surprisingly well (Fig. 19). It is, therefore, reasonable

$$\frac{N\ (\ell)}{N_t} = 35.09 \ EXP \ (-967 \left(\frac{\ell}{.02344} - 1\right)^2)$$
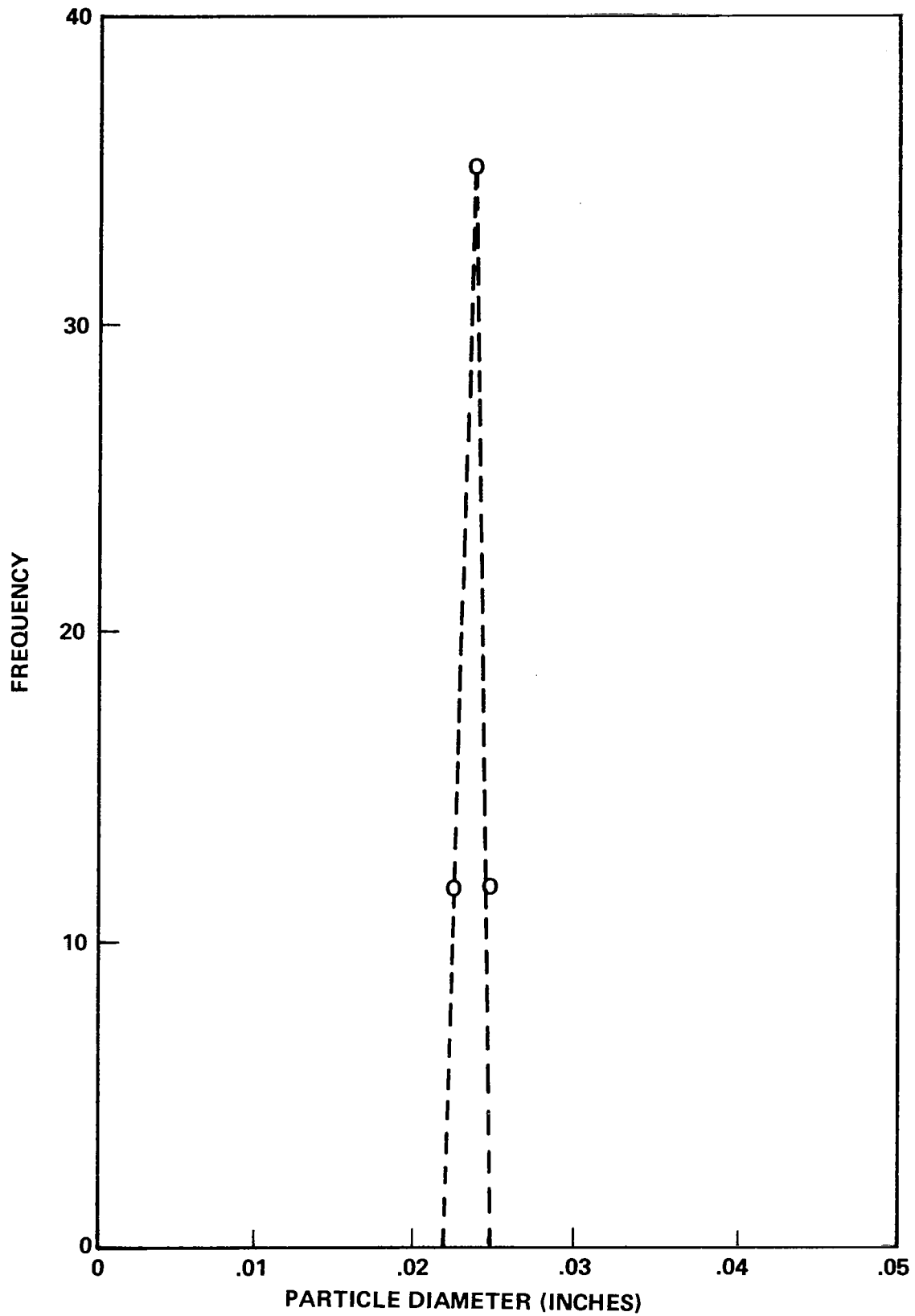
Figure 7. Glass beads particle diameter distribution.

$$\frac{N\,(\ell)}{N_t} = 261.9 \;\; \text{EXP.} \; \left(-5.3866 \left(\frac{\ell}{.005} - 1\right)^2\right)$$
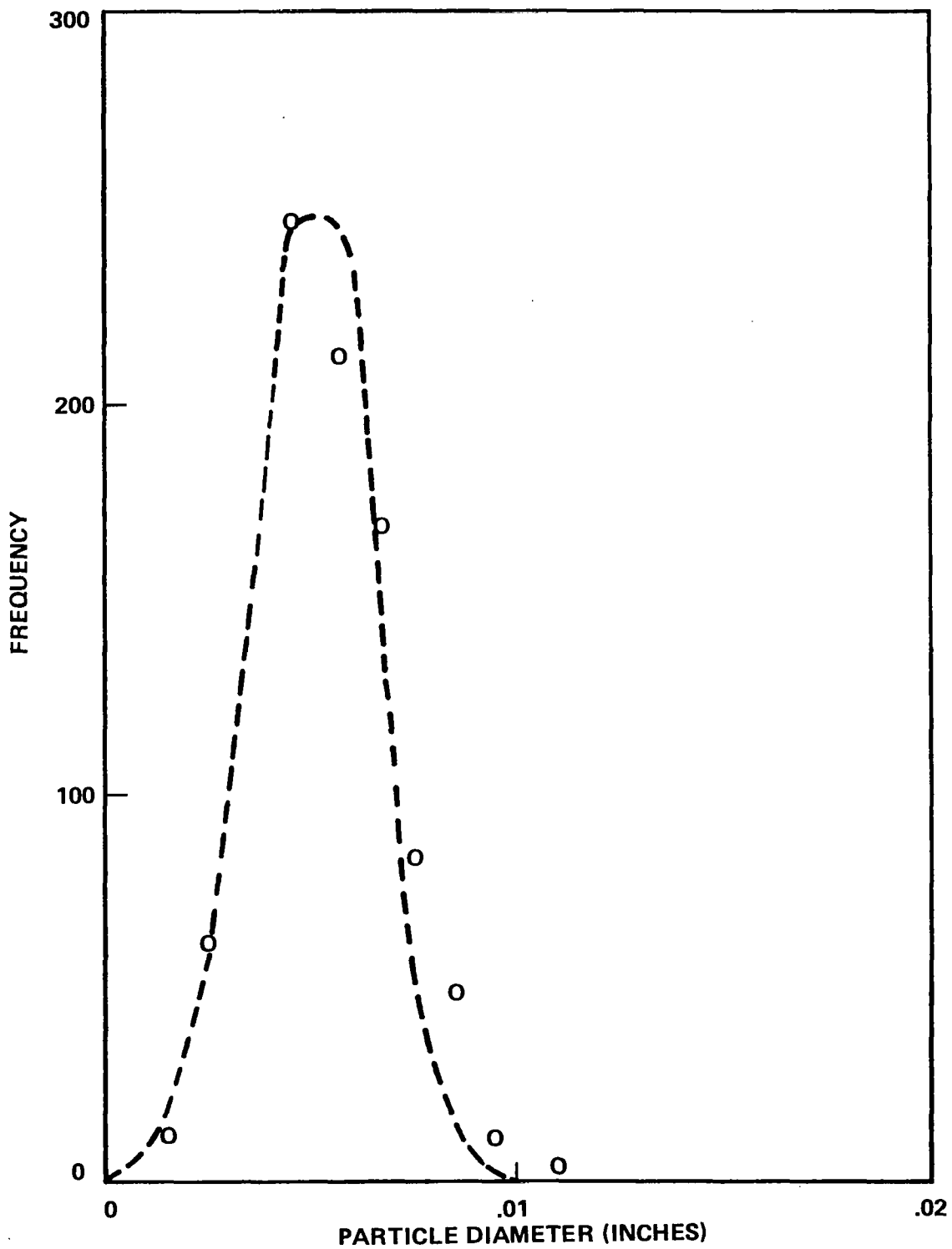

Figure 8. Superfine sandpaper particle diameter distribution.

$$\frac{N\,(\ell)}{N_t} = 279.4 \,\left(\text{EXP}.\,\left[\,-12.13\left(\frac{\ell}{.01}-1\right)^2\,\right] + 0.493\,\text{EXP};\,\left[-12.44\left(\frac{\ell}{.024}-1\right)^2\,\right]\,\right)$$
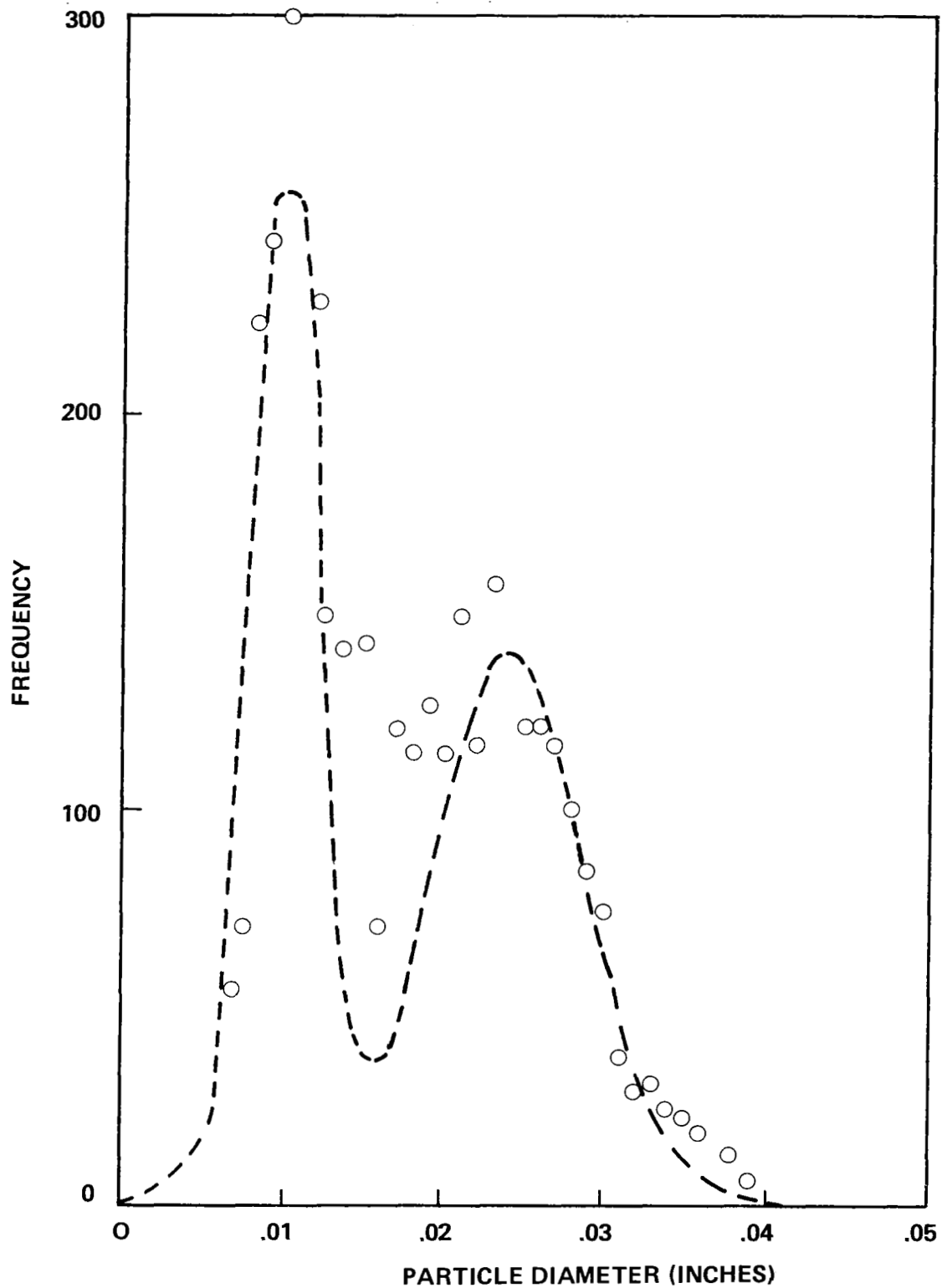

Figure 9. Fine sandpaper particle diameter distribution.

$$\frac{N(\ell)}{N_t} = 50.855 \ \text{EXP.} \ \left(-3.25 \left(\frac{\ell}{.02} - 1\right)^2\right)$$
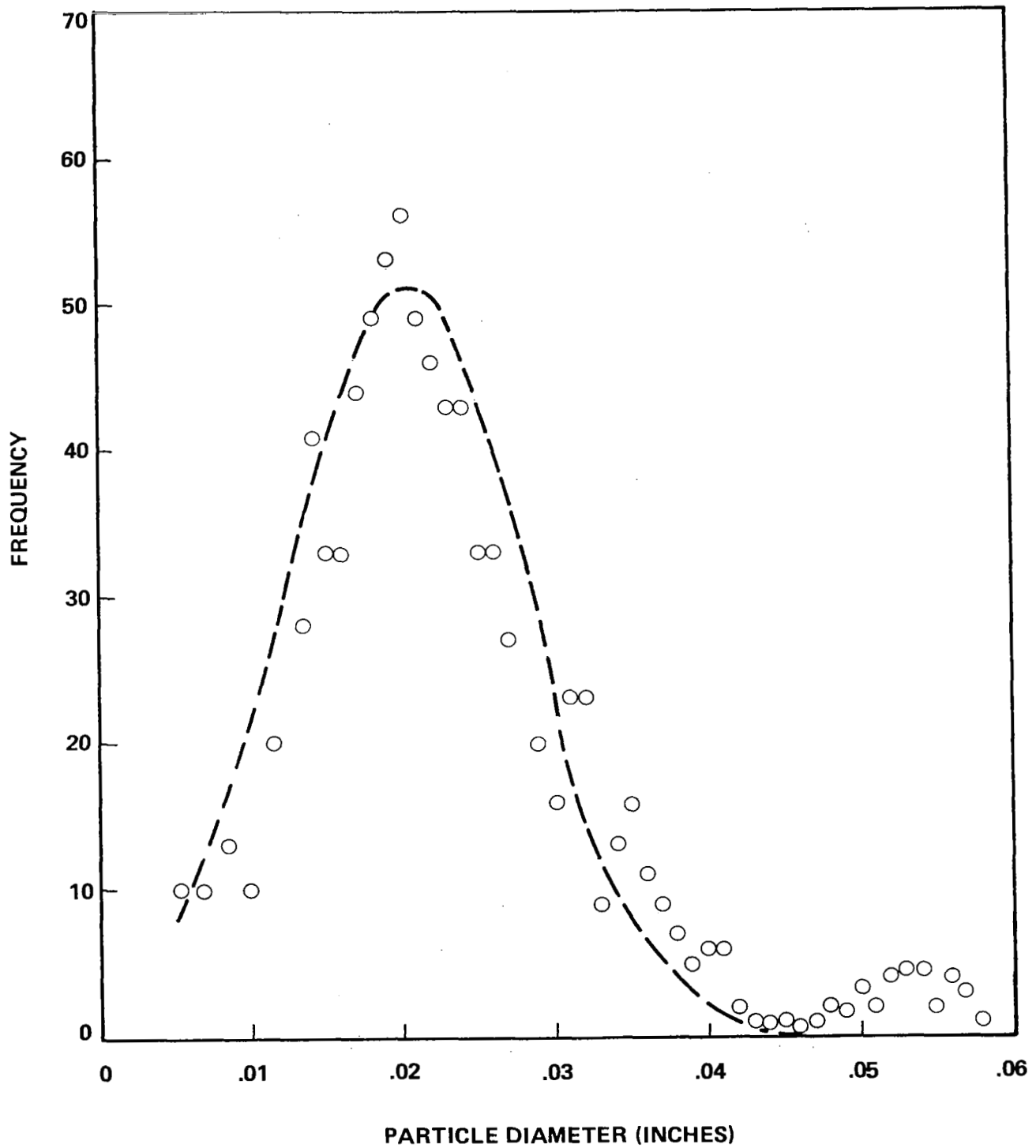
Figure 10. Coarse sandpaper particle diameter distribution.
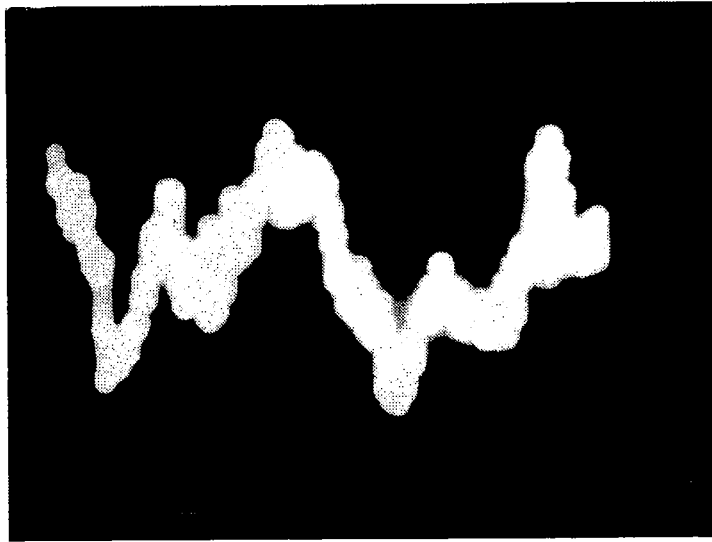
Figure 11. Photograph of velocity signal.
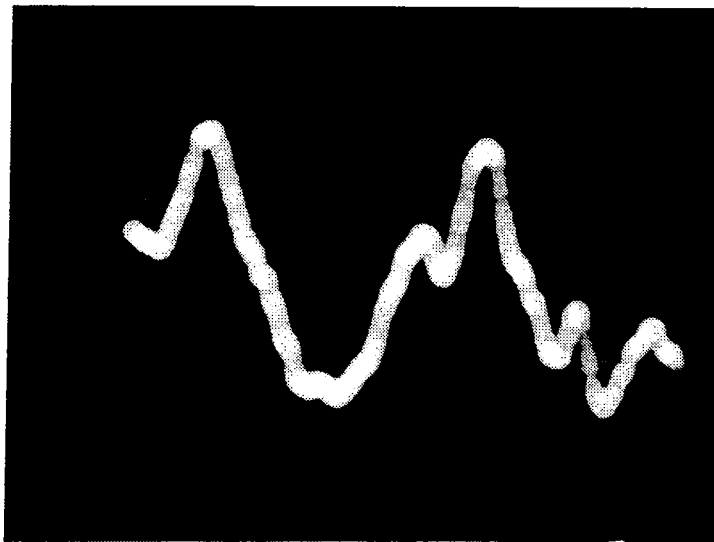
Figure 12. Photograph of velocity signal.
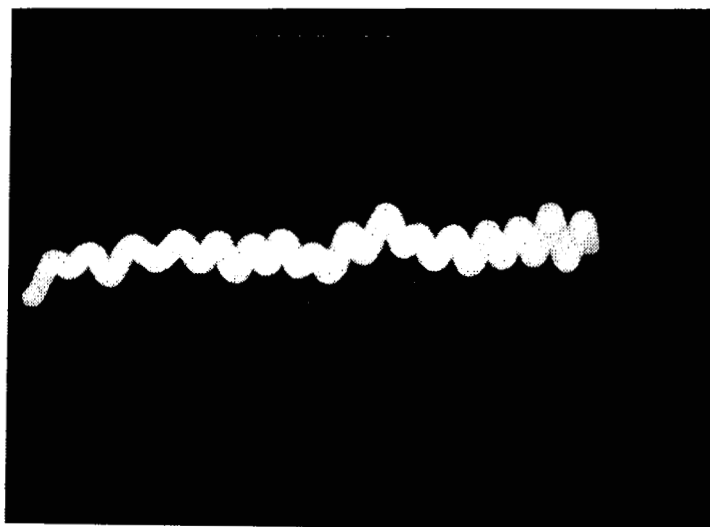
Figure 13. Photograph of velocity signal.
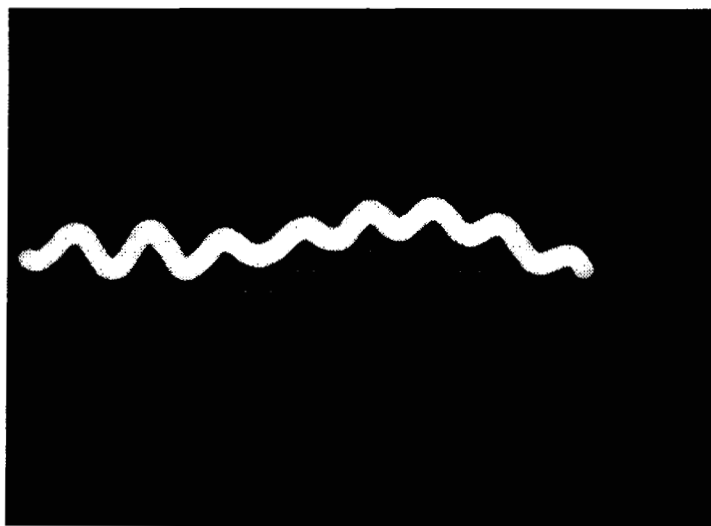
Figure 14. Photograph of velocity signal.
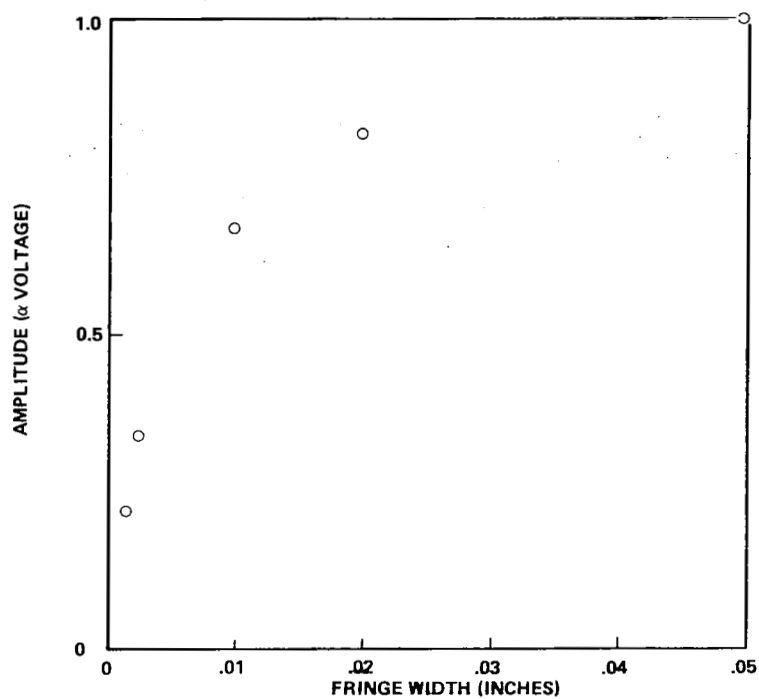
Figure 15. Amplitude data graphs: glass beads.

SUPERFINE SANDPAPER

$$I = 62,046 \, (\triangle X)^2 \, EXP. \, [-2 \, (243.9 \triangle X - 1)]$$
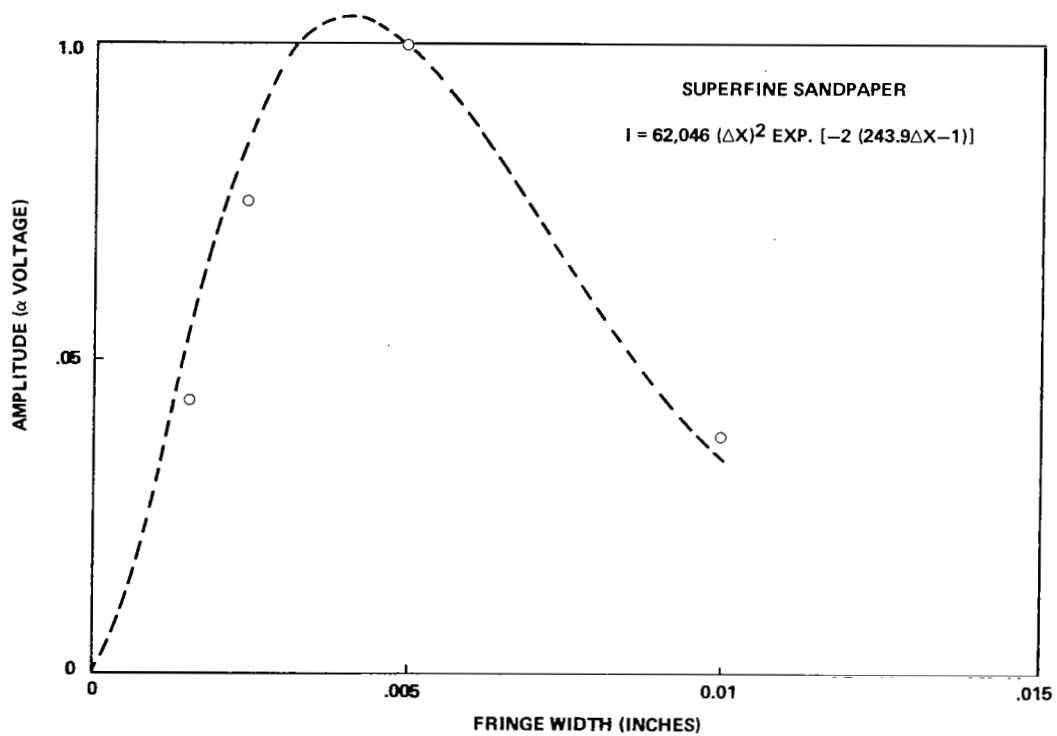
Figure 16. Amplitude data graphs: superfine sandpaper.

16
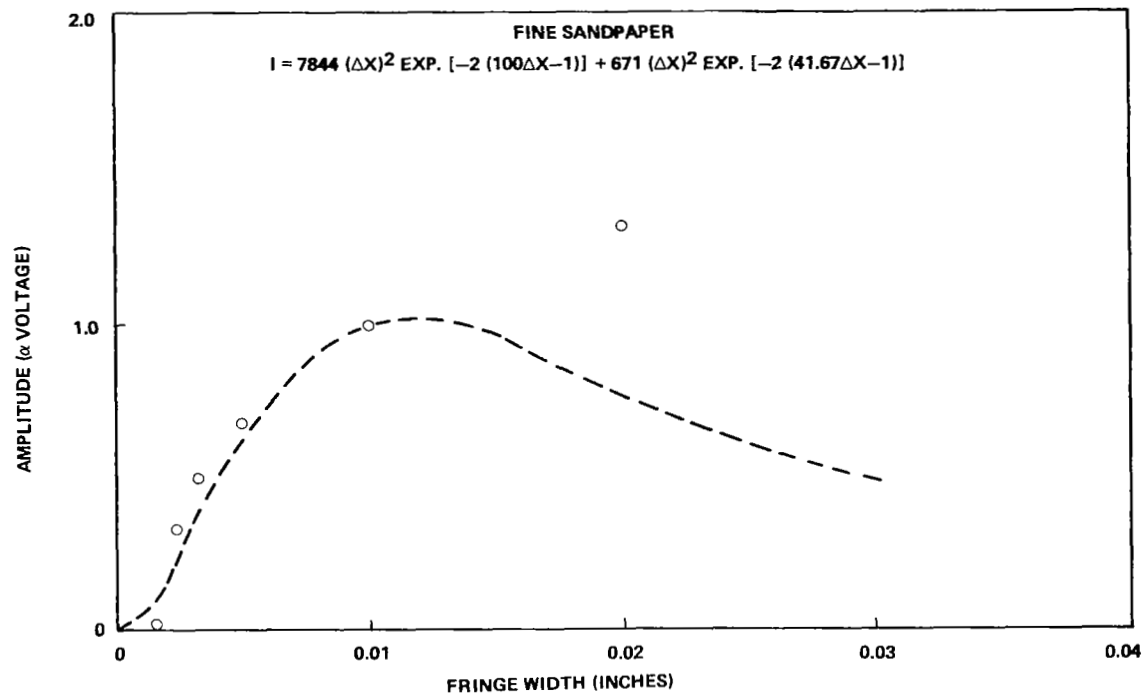
Figure 17. Amplitude data graphs: fine sandpaper.

FINE SANDPAPER

$I = 7844 \, (\triangle X)^2 \, EXP. \, [-2 \, (100 \triangle X - 1)] + 671 \, (\triangle X)^2 \, EXP. \, [-2 \, (41.67 \triangle X - 1)]$
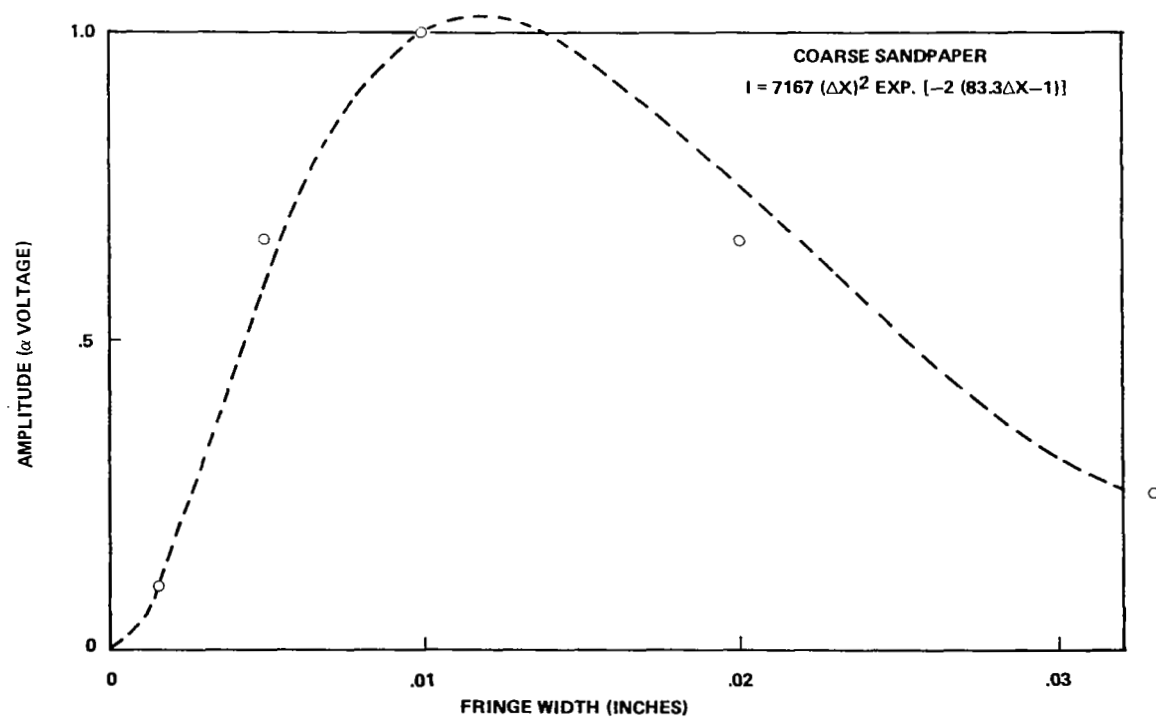
Figure 18. Amplitude data graphs: coarse sandpaper.

COARSE SANDPAPER

$I = 7167 \, (\triangle X)^2 \, EXP. \, [-2 \, (83.3 \triangle X - 1)]$
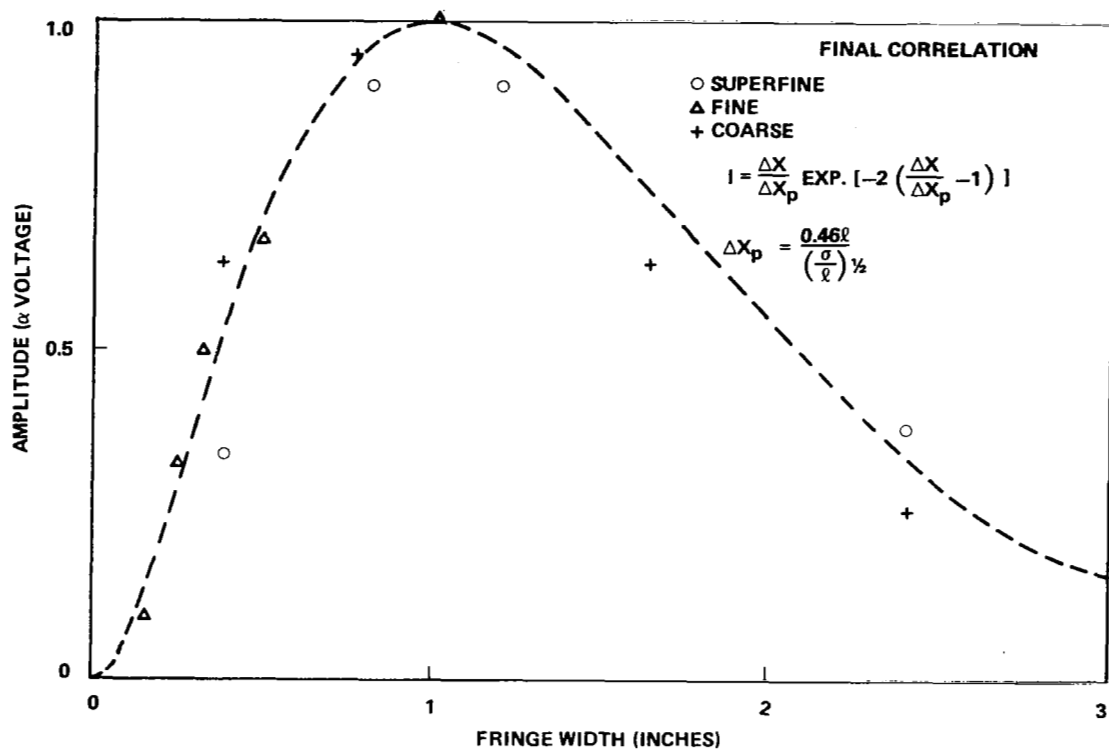
Figure 19. Final correlation.

TABLE 2. STATISTICS

Medium	Mean	Variance	Standard Deviation
Coarse sandpaper	0.02387	0.0001144	0.0106957
Fine sandpaper	0.01693	0.0000591	0.0076876
Superfine sandpaper	0.00568	0.0000053	0.0023021
Glass beads	0.02344	0.0000019	0.0013784

to conclude that either the amplitude ratio is only a function of the dimensionless fringe width or variables or groups of variables not included in the dimensionless fringe width are not of sufficient range to produce variations in the amplitude ratio greater than the experimental error.

The fringe width corresponding to the maximum amplitude ratio was correlated as a function of the variance and mean diameter of the particle size distribution. The equation is:

$$\frac{(\Delta X)}{\overline{\ell}} = 0.46 \left/ \left(\frac{\sigma}{\ell}\right)^{\frac{1}{2}}\right. \tag{2}$$

18

This appears to be the only variable that can be justifiably correlated with the data presented herein. One must conclude, therefore, that the amplitude ratio is not unique. A specified normal particle size distribution is sufficient, but not necessary to specify the amplitude ratio. An additional measurement must be made with which one can obtain an independent correlation of σ and/or $\bar{x}$ in order to specify a normal distribution.

Preliminary measurements of the fraction of the time that the velocity signal is detectable indicates that this data may provide the additional correlation required. This ratio should be proportional to the probability that the distribution is not significantly different between fringes at any given time.

B. Velocity Measurements

The technique for measuring velocity with the projected grating is the same as with laser Doppler velocimeters. In both cases, the frequency of the sinusoidal signal produced by the photomultiplier or photodiode is proportional to the velocity of the particles. The equations relating to velocity are derivable from first principles, so calibration is not necessary in either case. The difference is in the manner in which the fringe pattern is produced. The laser Doppler velocimeter has the advantage that the velocity of smaller particles can be measured (submicron range). The projected grating technique, however, is simpler and is adaptable to white light sources.

The relationship between particle velocity and frequency for the projected fringe system is simply:

$$V = \frac{1}{N_r} f \tag{3}$$

where

V = velocity in m/sec

N_r = fringes/m

f = frequency in cycles/sec.

Since this is a first principle measurement, frequency was used to distinguish between noise and velocity signals (equivalent Doppler signal). Two different velocities were used for each test sample and each fringe width. Comparison of the velocities measured with the velocity signal and the two angular velocity settings are indicated with Table 3 and 4.

Calculation of velocities for theoretical values are as follows:

$$160 \text{ rpms:} \quad V = \frac{120 \text{ rpms } *2*\pi*(5/4) \text{ in.}*\text{ft}*\text{min}}{12 \text{ in.}*60 \text{ sec}}$$

$$V = 1.745 \text{ (ft/sec)}$$

19

869 rpms: $V = \dfrac{869 \text{ rpms} *2*\pi*(5/4) \text{ in.}*ft*min}{12 \text{ in.}*60 \text{ sec}}$

Frequencies were summed for a particular test medium. Using $V = f/600$, Table 3 was compiled.

TABLE 3. EXPERIMENTAL VALUES

Test Medium	160 rpm	869 rpm
Coarse sandpaper	2	8.9
Fine sandpaper	2	11
Glass beads	1.5	7.7
Superfine sandpaper	1.1	8
Overall average	1.65	8.9

Using P.E. = $((V_{theory} - V_{experimental})/V_{theory})*100$ and Table 3, Table 4 was compiled.

TABLE 4. PERCENT ERROR

Test Medium	160 rpm	869 rpm
Coarse sandpaper	17.6	6.3
Fine sandpaper	17.6	15.8
Glass beads	11.8	18.9
Superfine sandpaper	35.3	15.8
Overall average	3	6.3

VI. CONCLUSIONS

The conclusions are as follows:

1) The dimensionless amplitude of the velocity signal is not sufficient to specify a normal particle size distribution.

2) A normal particle size distribution is sufficient to specify the dimensionless amplitude of the velocity signal.

20

3) A second independent measurement must be obtained and functionally related to the variance and/or mean diameter of the particle size distribution in order to measure the distribution function.

4) The only difference between velocity measurements obtained with the projected fringe technique and laser Doppler velocimeters is the frequency to velocity conversion constant. The various electronic data processing systems developed for laser Doppler velocimeters are directly applicable to the projected fringe technique.

VII. RECOMMENDATIONS

The following steps are recommended for the second phase:

1) Obtain sufficient data to verify the relationship between the "on-off" time of the velocity signal and the mean diameter and variance of the particle size distribution function.

2) Obtain sufficient data for full range of the instrument to develop reliable error analysis.

3) Determine the electronics development that will be necessary to process the signals to measure particle size distributions.

REFERENCES

1. Durst, Melling, and Whitelaw: Principles and Practice of Laser-Doppler Anemometry. Academic Press, New York, 1976.

2. Hecht and Zajac: Optics. Addison-Wesley Publishing Co., Reading, Massachusetts, 1974.

3. Yeh, Y. and Cummins, H. Z.: Localized flow measurements with an He-Ne laser spectrometer. Applied Physics, Vol. 4, p. 176, 1964.

4. Goldstein, R. J. and Hagen, W. F.: Turbulent flow measurements utilizing the Doppler shift of scattered laser radiation. Physics of Fluids, Vol. 10, p. 1349, 1967.

5. Welch, N. E., and Tomme, W. J.: Analysis of turbulence from data obtained with a laser velocimeter. AIAA Paper No. 67-179, 1967.

6. Pike, E. R., Jackson, D. A., Bourke, P. J., and Page, D. I.: Measurement of turbulent velocities from the Doppler shift in scattered laser light. Journal of Physics E, Vol. 1, p. 111, 1968.

7. Lewis, R. D., Foreman, J. W., Watson, H. J., and Thornton, J. R.: Laser-Doppler velocimeter for measuring flow-velocity fluctuations. Physics of Fluids, Vol. 11, p. 433, 1968.

8. Huffaker, R. M., Fuller, C. E., and Lawrence, T. R.: Application of laser-Doppler velocity instrumentation to the measurement of jet turbulence. S. A. E. Conference, Detroit, 1969.

9. Denison, E. B., Stevenson, W. H., and Fox, R. W.: Pulsating laminar flow measurements with a directionally sensitive laser velocimeter. American Institute of Chemical Engineering Journal, Vol. 17, p. 781, 1971.

10. Goldstein, R. J. and Kreid, D. K.: Measurement of velocity profiles in simulated blood by laser-Doppler techniques. ISA Symposium of Flow, Paper No. 4-2-95, 1971.

11. Anderson, R. E., Edlund, C. E., and Vanzant, B. W.: Measurement of particle velocity at a shock front in water with a laser-Doppler meter. Journal of Applied Physics, Vol. 42, p. 2741, 1971.

12. Jackson, D. A. and Paul, D. M.: Measurement of supersonic velocity and turbulence by laser anemometry. Journal of Physics E, Vol. 4, p. 173, 1971.

13. Jackson, D. A. and Paul, D. M.: Measurement of supersonic velocity and turbulence by laser anemometry. Proceeds of the First International Workshop on Laser Velocimetry, Purdue University, p. 487, 1972.

14. Lee and Srinivasan: Journal of Multiphase Flow, Vol. 4, p. 144, 1978.

15. Durst, F. and Whitelaw, J. H.: Measurements of mean velocity, fluctuating velocity, and shear stress using a single channel anemometer. DISA 12, Vol. 11, 1971.

16. Rudd, M. J.: Velocity measurements made with a laser-Doppler meter on the turbulent pipe flow of a dilute polymer solution. Journal of Fluid Mechanics, Vol. 51, p. 673, 1972.

17. Lennert, A. E., Trolinger, J. D., and Smith, F. H.: Applications of electro-optic techniques for jet and wake flow-field investigations. Arnold Engineering Development Center Report, 1972.

18. vom Stein, H. D. and Pfeifer, H. F.: Investigation of the velocity relaxation of micron sized particles in shock waves using laser radiation. Applied Optics, Vol. 11, p. 305, 1972.

19. Blake, K. A. and Jesperson, K. I.: The NEL laser velocimeter. NEL Report No. 510, 1972.

20. Durst, F., Melling, A., and Whitelaw, J. H.: Laser anemometry: a report on Euromech 36. Journal of Fluid Mechanics, Vol. 56, p. 143, 1972.

21. Durst, F., Melling, A., and Whitelaw, J. H.: The application of optical anemometry to measurements in recirculating flows and flames. DISA Conference on Fluid Dynamics, Measurements in Industrial and Medical Environments, paper II, p. 2-2, 1972.

22. Durst, F., Melling, A., and Whitelaw, J. H.: The application of laser anemometry to measurements in combustion systems. Combustion and Flames, Vol. 18, 1972.

23. Durst, F., Melling, A., and Whitelaw, J. H.: Laser anemometry measurements in a square duct with and without combustion oscillations. Imperial College, Mechanical Engineering Department, Report EHT/TN/A/40, 1972.

24. Durao, D. F. G., Durst, F., and Whitelaw, J. H.: Optical measurements in a pulsating flame. Journal of Heat Transfer, Vol. 95, p. 277, 1973.

25. Farmer, W. M.: Measurement of particle size, number density, and velocity using a laser interferometer. Applied Optics, Vol. 11, p. 2603, 1972.

26. Baker, R. J., Bourke, P. J., and Whitelaw, J. H.: Measurements of instantaneous velocity in laminar and turbulent diffusion flames using an optical anemometer, 1973.

27. Baker, R. J., Bourke, P. J., and Whitelaw, J. H.: The application of laser anemometry to the measurement of flow properties in industrial burner flames. Proceeds of the 14th Combustion Symposium, p. 699, 1973.

28. Yanta, W. J.: AIAA Paper No. 73-705, 1973.

29. Riethmuller and Ginoux: The application of a laser velocimeter to the velocity measurement of solid particles pneumatically transported, 1973.

30. Farmer, W. M.: Applied Optics, Vol. 13, p. 610, 1974.

31. Wigley, G.: Journal of Physics E, Vol. 11, p. 639, 1978.

32. Roberds, D. W.: Applied Optics, Vol. 16, p. 1861, 1977.

33. Birchenough, A. and Mason, J. S.: Journal of Powder and Bulk Solids Technology, Vol. 1, p. 6, 1977.

34. Birchenough, A., and Mason, J. S.: An industrial application of the laser velocimeter in gas-solid flows, 1977.

35. Oertel and Kirchartz: Applied Optics, Vol. 17, p. 22, 1978.

36. Ungut, Taylor, Yule, and Chigier: Journal of Energy, Vol. 2, p. 330, 1978.

37. Ungut, Yule, Taylor, and Chigier: Simultaneous velocity and particle size measurements in two phase flows by laser anemometry, a paper, 1978.

38. Cline and Crosswy: A survey of laser-Doppler velocimeter applications at the Arnold Engineering Development Center, 1979.

39. Birchenough, A., Andrews, D. G. H., and Mason, J. S.: Laser-Doppler velocity measurements in gas-solid flows. Thames Polytechnic, London, 1980.

40. Fridman, J. D., Huffaker, R. M., and Kinnard, R. F.: Laser-Doppler systems measure three-dimensional velocity vector and turbulence. Laser Focus, Vol. 4, p. 34, 1968.

41. Mazumder, M. K. and Wankum, D. L.: SNR and spectral broadening in turbulence structure measurement using a CW laser. Applied Optics, Vol. 14, p. 894, 1970.

42. Durst, F. and Whitelaw, J. H.: Integrated optical units for laser anemometry. Journal of Physics E, Vol. 4, p. 804, 1971.

43. Mazumder, M. K.: A symmetrical laser-Doppler velocity meter and its application to turbulence characterization. NASA CR-2031, 1972.

44. Wang, C. P. and Synder, D.: Laser-dopper velocimetry: Experimental study. Applied Optics, Vol. 13, p. 280, 1974.

45. Hanson, S.: Coherent detection in laser-Doppler velocimeters. Opto-electronics, Vol. 6, p. 263, 1974.

46. Adrian, R. J. and Goldstein, R. J.: Analysis of a laser-Doppler anemometer. Journal of Physics E: Scientific Instrumentation, Vol. 4, p. 505, 1971.

47. Asalor, J. O.: An examination of spectrum analysis for the processing of laser anemometer signals. Imperial College, Mechanical Engineering Department, Report HTS/73/46, 1973.

48. Deighton, M. O. and Sayle, E. A.: An electronic tracker of the continuous measurement of Doppler frequency from a laser anemometer. DISA, Vol. 12, p. 5, 1971.

49. Iten, P. D. and Mastner, J.: A laser-Doppler velocimeter offering high spatial and temporal resolution. Brown Boveri Res. Report KLR-71-07, 1971.

50. Fingerson, L.: Design considerations for a laser-Doppler anemometer. Proceeds of the Third Biennial Symposium on Turbulence in Liquids, Rolla, p. 220, 1973.

51. Smith-Saville, R. J.: Signal processor for use with laser-Doppler anemometer. Report from Cambridge Consultants Ltd., 1972.

52. Wilmhurst, T. H. and Rizzo, J. E.: An autodyne frequency tracker for laser-Doppler anemometer. Journal of Physics E, Vol. 7, p. 924, 1974.

53. Huffaker, R. M.: Laser-Doppler detection systems for gas velocity measurements. Applied Optics, Vol. 9, p. 1026, 1970.

54. Bourke, P. J., Brown, C. G., and Drain, L. E.: Measurements of spatial and temporal correlations of turbulence in water by laser anemometry. DISA, vol. 12, p. 17, 1971.

55. Farmer, W. M.: The interferometric observation of dynamic particle size, velocity and number density, Ph.D. Thesis, University of Tennessee, 1973.

56. Born, M. and Wolf, E.: Principles of Optics. Pergamon Press, Oxford, 1970.

57. Durst, F. and Eliasson, B.: Properties of laser-Doppler signals and their exploitation for particle size measurements. Proceeds of LDA-75 Symposium, Technical University of Denmark, 1975.
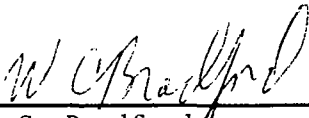
APPROVAL

DEVELOPMENT OF A SIMPLIFIED OPTICAL TECHNIQUE FOR THE SIMULTANEOUS MEASUREMENT OF PARTICLE SIZE DISTRIBUTION AND VELOCITY

By James Lee Smith

The information in this report has been reviewed for technical content. Review of any information concerning Department of Defense or nuclear energy activities or programs has been made by the MSFC Security Classification Officer. This report, in its entirety, has been determined to be unclassified.

W. C. Bradford
Director, Information and Electronic Systems Laboratory

1. REPORT NO. NASA TP-2185	2. GOVERNMENT ACCESSION NO.	3. RECIPIENT'S CATALOG NO.
4. TITLE AND SUBTITLE Development of a Simplified Optical Technique for the Simultaneous Measurement of Particle Size Distribution and Velocity		5. REPORT DATE June 1983
		6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) James Lee Smith		8. PERFORMING ORGANIZATION REPORT #
9. PERFORMING ORGANIZATION NAME AND ADDRESS George C. Marshall Space Flight Center Marshall Space Flight Center, Alabama 35812		10. WORK UNIT NO. M-413
		11. CONTRACT OR GRANT NO.
12. SPONSORING AGENCY NAME AND ADDRESS National Aeronautics and Space Administration Washington, D.C. 20546		13. TYPE OF REPORT & PERIOD COVERED Technical Paper
		14. SPONSORING AGENCY CODE

15. SUPPLEMENTARY NOTES

Prepared by Information and Electronic Systems Laboratory, Science and Engineering Directorate.

16. ABSTRACT

In an effort to develop a low cost, simplified optical technique for measuring particle size distributions and velocities in fluidized bed combustors and gasifiers, a two-phase research project was initiated at the University of Tennessee at Chattanooga. Phase One, the object of this report, consisted of the following:

1) Existing techniques were surveyed.

2) An experimental procedure was developed.

3) A laboratory test model was fabricated.

4) Limited data was recovered for proof of principle.

5) The relationship between particle size distribution and amplitude measurements was illustrated.

A He-Ne laser illuminated Ronchi Rulings (range 10 to 500 lines per inch). Various samples of known particle size distributions were passed through the fringe pattern produced by the rulings. A photomultiplier tube converted light from the fringe volume to an electrical signal which was recorded using an oscilloscope and camera. The signal amplitudes were correlated against the known particle size distributions. The correlation holds true for various samples.

17. KEY WORDS Laser Doppler Anemometry Multiple Particle Sizing Simplified Particle Sizing Technique	18. DISTRIBUTION STATEMENT Unclassified – Unlimited Subject Category 74
19. SECURITY CLASSIF. (of this report) Unclassified	20. SECURITY CLASSIF. (of this page) Unclassified	21. NO. OF PAGES 31	22. PRICE A03

National Aeronautics and
Space Administration

Washington, D.C.
20546

Official Business
Penalty for Private Use, $300

1   1 1U,H,   830613 S00903DS
DEPT OF THE AIR FORCE
AF WEAPONS LABORATORY
ATTN: TECHNICAL LIBRARY (SUL)
KIRTLAND AFB NM 87117

NASA