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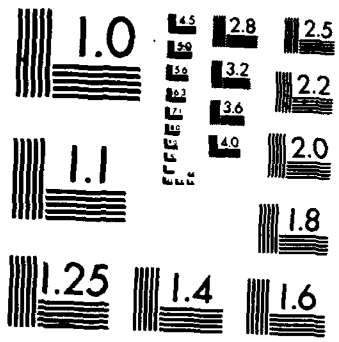

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19. Abstract

The fundamental scientific issues impeding the integration of laser diffraction particle sizing techniques into intelligent sensors for next-generation propulsion systems have been identified. This objective of this research is to contribute to the knowledge base necessary to significantly advance the laser diffraction concept. The research addresses three areas, inverse scattering algorithms, multiple scattering, and the problems of laser beam deflections due to refractive index gradients in hostile propulsion environments. Significant progress has been made in the development of direct integral transform techniques for the inverse problem which potentially can operate at frequencies on the order of 10 kHz as needed for propulsion system sensors. Adequate inversion performance on bi-modal distributions with signal-to-noise ratios as low as 10% has been demonstrated. Concerning multiple scattering, the problem has been formulated as a matrix operation, and a corresponding scheme for the inversion of diffraction data under multiple scattering conditions has been proposed. A prototype computer-generated hologram which generates a hollow cone of scattered light has been fabricated. Experiments are underway to demonstrate the usefulness of this development to the inverse multiple scattering problem. Finally, a concept to allow laser diffraction particle sizing sensors to function autonomously in environments where transient beam deflections are significant has been proposed and proof of principle experiments have begun.

AFOSR-TR- 86-1086

RESEARCH ON CERTAIN ASPECTS OF LASER DIFFRACTION PARTICLE SIZE ANALYSIS RELEVANT TO AUTONOMOUS SELF-DIAGNOSING INSTRUMENTATION

Annual Report for 1 Oct 1984 - 1 Oct 1985
AFOSR Grant 84-0187

By
E. Dan Hirleman and Joseph H. Koo
Mechanical and Aerospace Engineering Department
Arizona State University
Tempe, AZ 85287

Research Objectives

Particle and droplet size distributions, being parameters of fundamental importance, should be priority measurement objectives for intelligent sensors in next generation propulsion systems. Unfortunately there are a number of problematic scientific issues impeding the development of laser light scattering particle sizing instruments capable of on-line, autonomous, and self-diagnosing operation in hostile environments. The objective of this research effort is to contribute to the scientific knowledge base necessary to characterize and hopefully extend the applicability of laser diffraction instruments under these adverse conditions. Both the novel specific approaches discussed below and the emphasis on concepts relevant to intelligent instruments and sensors make this research project unique.

Our concept of a next-generation laser diffraction system is shown in Fig. 1 where the light scattered in the near-forward direction (i.e. diffracted) by particles along the line-of-sight of the probe laser beam is collected by a lens and sensed in the back focal (Fourier transform) plane. The diffraction reference leg, variable focal length transform lens, beam position detector, and a dynamically configurable ring detector array are novel concepts proposed here to extend the standard configuration of laser, beam expander, fixed focal length transform lens, and fixed geometry detector. We envision an intelligent instrument which performs self-calibration, self-diagnosis, and monitors the operating environment in order to automatically reconfigure the detector geometry and inverse scattering algorithm to maintain operation near an optimal state. In the original proposal submitted to AFOSR in 1984 we identified three research areas in which the lack of scientific understanding would limit future advances. In the following paragraphs we discuss the research objectives associated with each of these target areas.

1. Inverse Scattering Algorithms

Particle sizing using laser (Fraunhofer) diffraction is an inverse scattering problem. The governing equation for single scattering by large particles is a Fredholm integral equation:

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$$I(\theta) = \lambda^2/4\pi^2 \ (I_{inc}/\theta^2) \int_0^\infty J_1{}^2(\alpha\theta) \ \alpha^2 \ n(\alpha) \ d\alpha \qquad (1)$$

where: $\alpha = \pi d/\lambda$ is the particle size parameter; $n(\alpha)$ is the unknown particle size distribution; and $I(\theta)$ the scattering intensity which can be measured at some number of scattering angles. Unfortunately the presence of $n(\alpha)$ inside the integral of Eq. (1) makes the problem ill-posed in the sense that small variations in the measurements of $I(\theta)$ (e.g. due to noise) can cause large changes in the resulting $n(\alpha)$. The maximum information obtainable about $n(\alpha)$ is dependent on the noise levels in the measurements, the sampling or detection scheme, the stability or robustness of the inversion method, the actual size distribution, and the allowable level of uncertainty. Ideally, then, a laser diffraction system would have variable detector geometry, inversion scheme, and size resolution which could all be adjusted at run time depending on the conditions encountered.

The objective of this part of the research is to identify and impact the underlying scientific issues which presently impede the needed quantum improvements in efficiency and robustness of inversion schemes for intelligent laser diffraction sensors. Dynamic adaptive control of the detector configuration, synergism of the inversion scheme and detector geometry are major focus areas.

2. Multiple Scattering.

A major challenge for future research on *in-situ* optical techniques for particle sizing is to extend application of these methods into the regime of optically thick media. The theoretical framework for particle size measurements under multiple scattering conditions is rather tenuous, even for the direct problem of calculating the radiation transfer properties of an arbitrary particulate medium. Even less developed are analytical methods for the inverse problem, *i.e.* obtaining particle size distribution information from measured optical scattering properties of media where multiple scattering is significant.

The objective of this part of the research is to understand the process of multiple scattering as it might occur in future applications of intelligent particle size distribution sensors and develop inversion schemes which can operate in such an environment. A minimum requirement is that the presence of multiple scattering be diagnosed by the instrument to ensure that erroneous data not be used in control algorithms, a situation which could result in a catastrophic failure. Our objective is to surpass that and develop efficient and robust algorithms which can actually extract useful particle size information from Fraunhofer diffraction measurements in multiple scattering environments.

3. Laser Beam Deflection/Steering

Another problem which has already limited the usefulness of laser diffraction particle sizing instruments in propulsion systems research is that of beam deflection by refractive index gradients in the optical path. These gradients are due to spatially nonuniform temperature and/or species concentrations and at relatively large scales have the same effect as an array of randomly dispersed and time-varying lenses which cause the probe beam to move around at the detection plane. This has been a severe problem since information on the largest droplets in typical sprays is concentrated at small scattering angles which are of the same order as the beam deflection angles encountered.

The objective for this research topic is to investigate concepts which could enable a laser diffraction instrument to operate under conditions where beam deflection is significant. A minimal requirement is for on-line detection of beam steering so that an intelligent instrument would at least know that the data taken under these conditions is suspect. A more important objective is to develop strategies to permit a diffraction system to autonomously perform real-time correction for beam steering.

Status of the Research Effort

Significant progress has been made in each of these areas over the duration of this grant and we foresee no significant deviations from the original approach proposed for the research. The sections below describe the technical achievements made in these areas during the indicated 12 month time period.

1. Inverse Scattering Algorithms

The inverse scattering problem for laser diffraction particle sizing instruments has similarities with all systems requiring a deconvolution of experimental data. The inverse scattering problem (i.e. determination of $n(\alpha)$ in Eq. (1) from measured $I(\theta)$) can be solved by either (i) direct integral transform methods or (ii) indirect numerical quadrature approaches. In the past year we have concentrated on the generally overlooked integral transform techniques which, by virtue of the direct nature, have unique potential for very fast solutions as would be required by an on-line, intelligent sensor. The general integral transform solution to Eq. (1) is:

$$n(\alpha) = c/\alpha^2 \int_{\theta_{min}}^{\theta_{max}} h_x(\alpha\theta)\, X(\theta)\, d\theta \qquad (2)$$

where: c is a constant, h_x is the transform kernel, X is some function of the experimental data, and the specific forms of X and h_x are coupled. The most straightforward solution to Eq. (2) obtains an $X(\theta)$ proportional to the derivative of $I(\theta)$. Integration of Eq. (2) by parts produces other functions X (and associated functions h_x) which involve integrals of $I(\theta)$. We have initiated a thorough study of the integral transform formulations applicable to the inverse Fraunhofer diffraction problem and identified four unique methods. The methods are identified by the primary author as: (i) Chin (1955), (ii) Shifrin-Kolmakov I (1967), (iii) Shifrin-Kolmakov II (1967), and (iv) Petrov (1976/1985). Only for the method of Chin had complete studies of inversion performance been previously made.

In order to establish a framework to evaluate existing and new transform methods we have developed a set of benchmark problems. These benchmark data sets permit numerical studies/simulations of the performance of various techniques under controlled and realistic conditions. In general, there are six major parameters that will affect the inversion of laser diffraction data. They are (a) minimum scattering angle θ_{min}, (b) maximum scattering angle θ_{max}, (c) angular resolution $\Delta\theta$, (d) noise level, (e) out of range particles, and (f) numerical techniques for integration and differentiation. As a part of this research we have studied inversion results obtained for assumed bi-modal and tri-modal log normal particle size distributions as a function of these six parameters.

An important property of an inversion algorithm is immunity to experimental measurement error or noise. Figure 2 indicates the results of a Chin inversion of synthetic scattering data perturbed by several forms of synthetic noise. The results are reasonably good, even for the rather large levels of noise used in the simulations. The other integral transform methods perform in a manner similar to that shown in Fig. 2 and the results are documented in the publications listed below.

2. Multiple Scattering

A solution to the inverse multiple scattering could be obtained if an instrument could ascertain which photons reaching the detector plane had been scattered once and only once. This single scattering data could then be inverted using methods based on Eq. (1) as discussed above. Unfortunately we have been unable to suggest a method for performing this photon segregation directly. An indirect method we are developing involves viewing the effect of the multiple scattering medium as a matrix operation such that:

$$S_{mult} = M \cdot S_{single} \quad (3)$$

where: S_{mult} and S_{single} are vectors with each element representing the scattering signal collected for one of the ring detectors of Fig. 1 and the subscripts indicate multiple and single scattering respectively; and M is a square matrix which represents the multiple scattering characteristics of the medium. S_{mult} is the scattering signature which would be measured directly by a laser diffraction system. M_{ij} represents the efficiency by which the medium of interest redistributes that single scattered energy which would have reached the jth detector (under optically thin conditions) into the ith detector. If the matrix **M** could be measured, then the effective single scattering signature S_{single} could be determined by inverting **M**:

$$S_{single} = \mathbf{M}^{-1} \cdot S_{mult} \qquad (4)$$

The size distribution could then be determined using a classical inversion of the effective single scattering signature using standard inverse Fraunhofer algorithms.

We have developed and are studying a method to measure the matrix **M** on-line. Consider a diffraction reticle of Fig. 1 which could generate a hollow cone of scattered light. This synthetic scattering signature would represent an input vector S_{single} with only one non-zero element. After this passed through the medium the diffraction signature at each detector due solely to the input scattering cone would be proportional to a corresponding element in a single column of **M** as seen in Eq. (3). Figure 3 is a computer-generated hologram designed to produce the hollow scattering cone. A series of scaled holograms like Fig. 3, one for each detector, provides a series of scattering vectors S, each with a different non-zero element. In that way **M** can, in theory, be characterized on-line. Our experiments to investigate the performance of the diffraction hologram are continuing.

3. Laser Beam Deflection/Steering

The probe laser beam from a Fraunhofer diffraction instrument will, in general, be continuously deflected as it traverses a medium of nonhomogeneous refractive index as would be encountered in a combustor. This causes the transmitted beam and the associated diffraction pattern which is centered around it to be directed to off-center points in the detector plane of Fig. 1. The very high intensity in the transmitted beam, which typically would be more than 100x greater than the intensity scattered into the small angle inner rings of the detector, severely hampers the measurements at small angles. One possible solution we are investigating is to measure the instantaneous position of the probe beam at the detector plane and dynamically configure as ring detector centered about that. We have obtained a position detector as shown in Fig. 1 and find that the time-response is adequate. Research into the remaining problem of configuring a detector in real-time is continuing.

Technical Presentation

1. E. D. Hirleman
   "Calibration Techniques for Laser Diffraction and Single Particle Counting Spray Sizing Instruments""
   Fifth ASTM Symposium on Pesticide Formulations and Application Systems, Kansas City, MO., November, 1984.

Technical Publications

1. E. D. Hirleman and L. G. Dodge
"Laser Diffraction Measurements of Sprays and Reticles: Accuracy and Interpretation"
Western States Section/Combustion Institute Spring Meeting, San Antonio, TX, April 1985, Paper 85-6.

2. E. D. Hirleman, E. Hovenac, and R. F. Ide
"Calibration and Sample Volume Characterization of PMS Optical Array Probes"
ICLASS '85 Proceedings, Paper 85-84, The Institute of Energy, London, England, July, 1985.

3. E. D. Hirleman and L. G. Dodge
"Performance of Laser Diffraction Drop Size Analyzers"
ICLASS '85 Proceedings, Paper 85-64, The Institute of Energy, London, England, July, 1985.

Personnel

Prof. E. Dan Hirleman - Associate Professor of Mechanical and Aerospace Engineering. Principal Investigator

Joseph H. Koo - Research Assistant and Ph.D student. Mr. Koo's dissertation will come out of this work and his Ph.D. should be awarded in 1986.

New Discoveries

1. Computer-generated Hologram for Diffraction Reference Signature

One new development resulting from this research is the concept of a computer-generated hologram to produce a diffraction reference signature which has only a single scattering order (i.e. scattering at a single angle). A first generation of this concept has been produced and a photographic reproduction is shown in Fig. 3. This concept is an important advance in the future development of inverse Fraunhofer diffraction schemes which may work in multiple scattering environments. The concept also has important implications for improvements in on-line calibration of laser diffraction instruments.

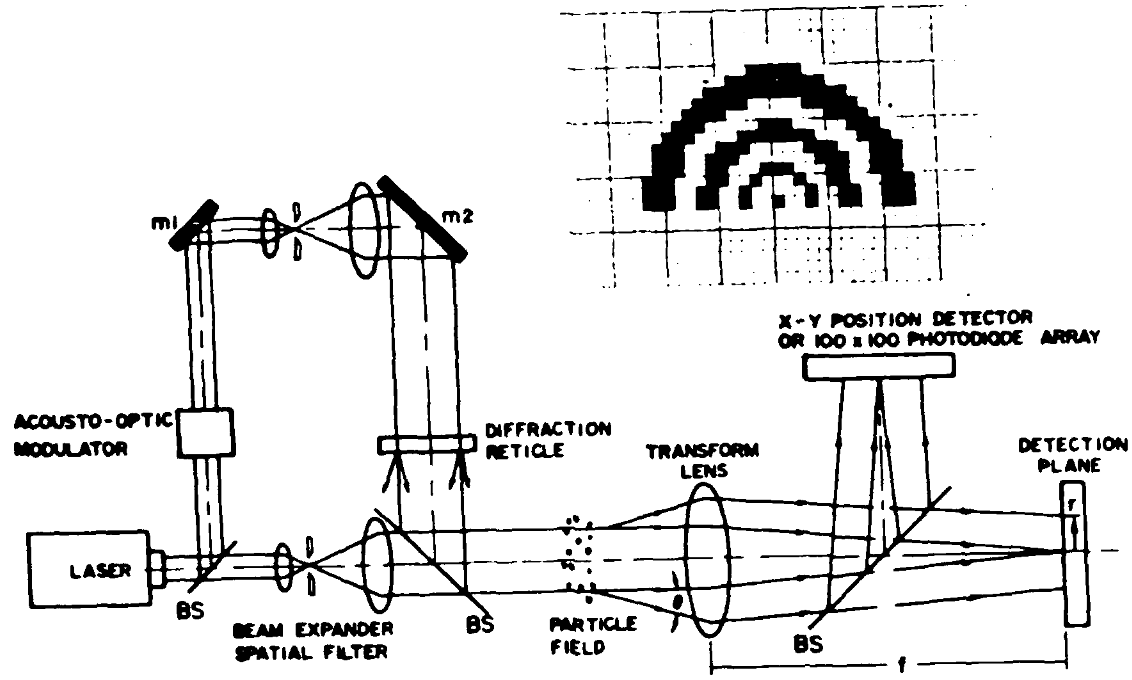

Fig. 1 Schematic of a next-generation laser diffraction particle sizing system for use as an intelligent sensor.

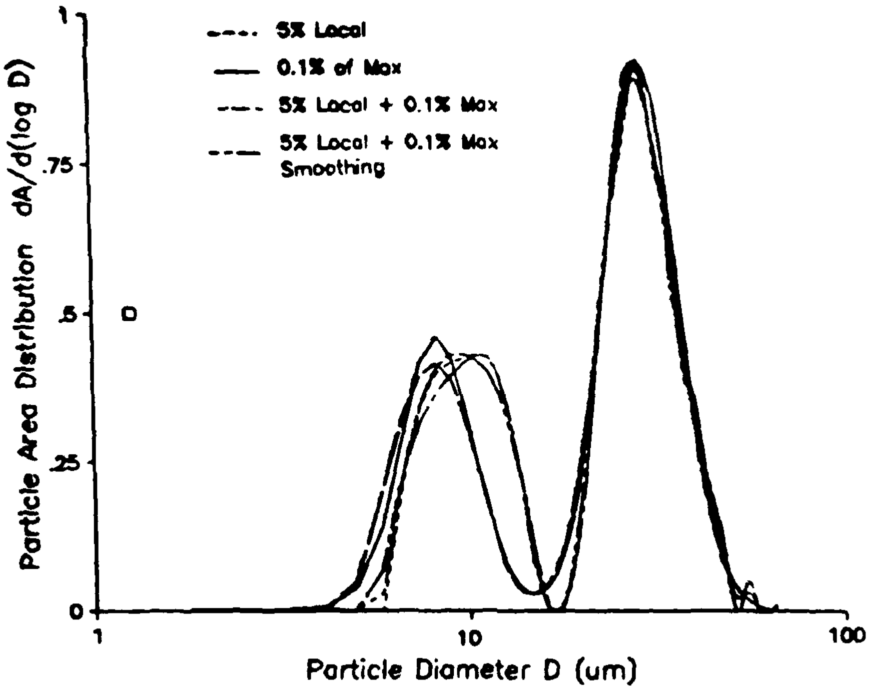

Fig. 2 Diffraction inversion results showing the effect of noise on the integral transform technique of Chin. The solid line shows the assumed bi-modal size distribution, and the dashed lines show the inversion results for the indicated noise levels.

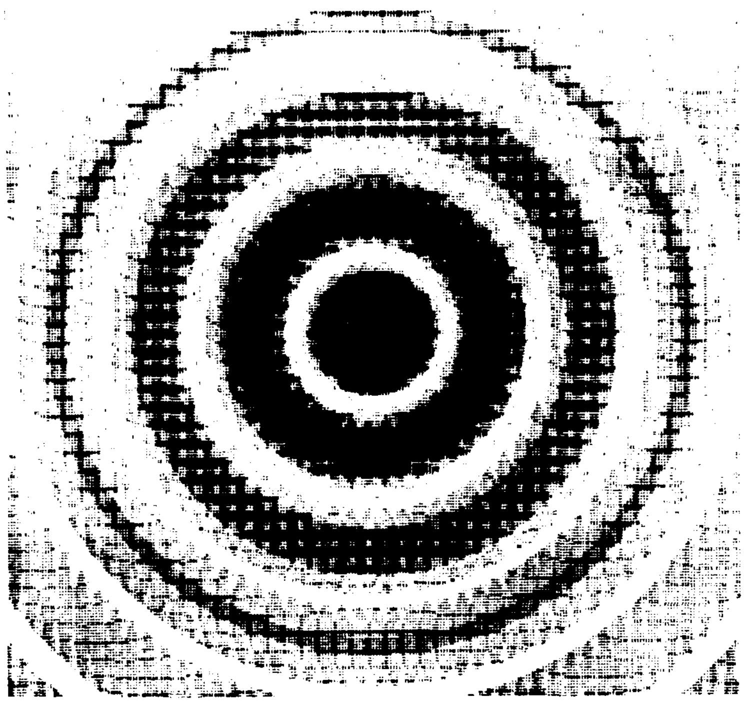

Fig. 3 Photographic reproduction of computer-generated hologram

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