Measurements of optical scattering of a light beam in passing through an axisymmetric heated turbulent jet

by Richard Lane Hogan

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Mechanical Engineering

Montana State University

Abstract:

Although considerable work has been done to theoretically predict the optical degradation of a light beam in passing through a turbulent medium, relatively little experimental work has been done. A heated axisymmetric jet was chosen as an optical scattering medium through which the beam was passed at differing, distances from the jet nozzle. The investigation was intended to determine the effectiveness of the given experimental set-up in demonstrating qualitatively various theoretically-predicted beam scattering effects including intensity attenuation, "jittering" angle, and deflection. The measured scattering effects were compared to results obtained using simplified prediction methods. The measured beam scattering data demonstrated distinct trends in the scattering properties of interest associated with various changes in the fluid properties of the turbulent medium.

The prediction methods and the simplifying assumptions used in their application however, provided a reliable qualitative standard of comparison for the case of beam deflection only. A more in-depth analysis would be required for increased confidence in the prediction of beam "jittering" angle and intensity attenuation.

MEASUREMENTS OF OPTICAL SCATTERING OF A LIGHT BEAM IN PASSING THROUGH AN AXISYMMETRIC HEATED TURBULENT JET

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APPROVAL

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This thesis has been read by each member of the thesis committee and has been found to be satisfactory regarding content, English usage, format, citations, bibliographic style, and consistency, and is ready for submission to the College of Graduate Studies.

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Date 5/13/88

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NOMENCLATURE

Symbol		Description
D	:	Nozzle diameter
f	:	Frequency
I	:	Electrical current
L	:	Jet characteristic length, Beam deflection distance
M	:	Jet momentum integral
n	:	Refractive index
R_o	:	Hot wire "zero current" resistance
T	:	Temperature
U	:	Velocity
X	:	Jet axial coordinate, Beam deflection
Y	:	Jet radial coordinate
$\tilde{Y}$	:	Modified jet radial coordinate
Z	:	Beam path coordinate
α	:	Hot wire thermal resistance coefficient, Optical extinction coefficient
Δ	:	Fluctuation
θ	:	Beam deflection angle
ϕ	:	Beam "jittering" angle, deflection angle
λ	:	Wavelength of light
η	:	Nondimensional radial jet coordinate

NOMENCLATURE--Continued

Symbol		Description
Λ	:	Turbulence scale
ρ	:	Density
τ	:	Hot wire time constant
$\overline{(\ )}^2$	:	Mean square quantity
(O)	:	Axis property (beam or jet)
$(\ )_o$	:	Property at 0 C
$(\ )_1$	:	Property at jet nozzle
$(\ )_\infty$	:	Property in jet surroundings
$(\ )_{RMS}$	:	Root-mean-square property
$(\tilde{\ })$	:	Nondimensional property
$\overline{(\ )}$	:	Nondimensional property

ABSTRACT

Although considerable work has been done to theoretically predict the optical degradation of a light beam in passing through a turbulent medium, relatively little experimental work has been done. A heated axisymmetric jet was chosen as an optical scattering medium through which the beam was passed at differing distances from the jet nozzle. The investigation was intended to determine the effectiveness of the given experimental set-up in demonstrating qualitatively various theoretically-predicted beam scattering effects including intensity attenuation, "jittering" angle, and deflection. The measured scattering effects were compared to results obtained using simplified prediction methods. The measured beam scattering data demonstrated distinct trends in the scattering properties of interest associated with various changes in the fluid properties of the turbulent medium. The prediction methods and the simplifying assumptions used in their application however provided a reliable qualitative standard of comparison for the case of beam deflection only. A more in-depth analysis would be required for increased confidence in the prediction of beam "jittering" angle and intensity attenuation.

CHAPTER 1

INTRODUCTION

In passing a beam of light through a region of turbulent density fluctuations an overall degradation of the beam optical quality occurs. The beam degradation occurs as a result of the index of refraction variations present which are directly related to the density variations within the turbulent medium. Degradation effects on the beam include an overall average deflection of the beam axis, attenuation of the beam intensity, and a "jittering" of the beam about its time-averaged position.

Initially the majority of the effort put forth in the area of turbulence-caused optical scattering was theoretical in nature and mainly involved atmospheric-type turbulence. Several papers presenting various analytical approaches to the problem were published in the mid-1960's, some of which compared the predicted scattering results to actual measurements. By the late 1960's growing interest was shown in various laser applications involving the passage of the beam through turbulent boundary-layer type flows. The turbulent medium for this type of situation differed in that it generally possessed higher turbulent frequencies and smaller turbulent scales than those encountered in atmospheric-type turbulence. Although a fair amount of theoretical work was done for optical scattering involving this type of turbulence with only a few notable exceptions very little experimental work was done.

The following investigation is experimental in nature and attempts to provide a qualitative indication of the optical scattering effects of a well-measured and documented turbulent medium on a laser beam. An experimental apparatus capable of producing easily-measured light beam optical scattering effects was to be designed and built. Equipment was required to produce the necessary turbulent medium, to direct a laser beam through the medium, and to make the necessary optical scattering measurements. Measurements of the turbulence properties were made in order to determine the nature of the refractive index fluctuations present for each of several turbulent flow cases considered. The intensity characteristics of the degraded beam corresponding to each flow case were also measured and used to determine beam scattering properties. A comparison was made of the measured beam scattering effects with predictions of the scattering effects obtained using the measured turbulence properties and simple theoretical relations. The beam scattering properties of interest included intensity attenuation, time-averaged deflection, and beam "jittering" angle, defined as the root-mean-square angular variation of the beam about its time-averaged position.

CHAPTER 2

THEORETICAL REVIEW

Much theoretical work was done in the 1960's on the topic of optical scattering of a beam of light induced by turbulent refractive index variation in the medium through which the beam passes. In 1961, Tatarski (11) gave a statistical description of wavefronts acted on by a turbulent medium. In his analysis, the random turbulent medium was treated as being "frozen" in time during the propagation of the wave. Then an average was taken over all possible turbulence arrangements in order to obtain the time-average effects of the turbulence. Hufnagel and Stanley (4) in 1963 approached the problem by describing the time-averaged turbulent effects with a mutual beam coherence factor. In 1965, DeWolf (5) compared and examined the ranges of validity for three approximations for forward scattering (scattering in the direction of wave propagation) for an image being transmitted through a "slab" region of turbulence. The approximations considered included the Geometric Optics approximation, First Born approximation, and the Rytov complex phase expansion. In this work the turbulent fluctuations were assumed to vary smoothly and be large in comparison to the light wavelength. Heidbreder and Mitchell (7) in 1966 made a comparison between light intensity distributions for two cases: (1) plane waves (light) incident on a circular, stationary aperture and (2) planes waves incident on a circular, wavefront-tracking aperture. In this analysis it was assumed that image fluctuations on the image plane corresponded predominantly to a random wavefront tilting in passing through the turbulent medium. Taylor (6) in 1966 expanded on the work of Hufnagel and Stanley. In his work terms of higher order that were neglected in the work of (4) were accounted for. The resulting mutual coherence factor describes the deterioration of the beam coherence in passing through a turbulent medium. All of the previous theoretical analysis assumed the turbulent medium to be homogeneous and isotropic and the light beam entering the turbulence to be initially plane. Sutton in 1969 predicted theoretically the attenuation and distribution of beam intensity in the far field (large distances beyond the turbulent medium) for the case of a beam, also traversing a homogeneous and isotropic turbulent medium. Time-averaged effects only were considered. Several different cases of extinction (αL) and D/Λ ratios were considered. α is the extinction coefficient of the turbulence, L is the scattering path length, D is the beam diameter and Λ

represents the turbulence scale. A method for the detection of wind tunnel boundary layer transition using a laser beam was published in 1976 by Demetriades and Laderman (1). The index of refraction variation occurring in the turbulent boundary layer caused a scattering of the beam, the nature of the scattering being dependent on the turbulence present in the boundary layer at the point where the beam traversed the boundary layer. Simple methods were given which allow the computation of beam scattering effects including attenuation, "jittering", and spreading of the beam pattern using experimentally-measured data. In 1979 Cudahy, Van Kuren, and Wright (8) performed measurements of beam scattering effects occurring as a result of a two-dimensional turbulent jet through which the beam was passed. Turbulence properties of the jet were not measured but were estimated from data taken from other similar jet experiments. Theoretically-predicted beam scattering results computed using the estimated turbulence properties were compared with experimentally measured scattering effects. Only beam attenuation was considered in the comparison. The attenuation prediction scheme, although fairly involved, provided good correlation with experimental attenuation measurements.

CHAPTER 3

EXPERIMENTAL APPROACH

The following experimental procedure provides measurements of the turbulence properties of the optical scattering medium as well as the laser beam intensity data required to determine the nature of the optical beam degradation resulting from the passage of the beam through each of several turbulent flow conditions considered.

Measurements of the turbulent flow necessary to determine the turbulent refractive index variations were made. A thermocouple probe was used to obtain mean temperature data within the jet. Hot wire anemometer-type temperature probes provided turbulent temperature data. A flow velocity probe utilizing two hot film probes was used to determine mean flow velocity distributions. Both axial and radial traverses within the jet were made with all three instruments in order to determine distributions of temperature and velocity within the jet.

The recorded laser beam intensity distribution data consisted of points taken along horizontal and vertical traverses of the degraded beam pattern using a light intensity detector. For each beam intersection point within the jet both mean and root-mean-square (RMS) intensity distributions in the scattered beam were recorded. A mean intensity distribution was also recorded for the case of an undisturbed beam (beam does not intercept a turbulent scattering medium). The measured beam intensity data was then used to compute beam degradation properties of interest (attenuation, "jittering" angle, and time-averaged deflection of the beam axis). The measured beam degradation properties were compared to results computed using the measured turbulence properties and simple theoretical beam optical scattering models.

CHAPTER 4

EXPERIMENTAL APPARATUS AND PROCEDURE

Jet Apparatus

An apparatus was constructed to heat ambient air, used as the jet medium, to the desired jet temperature. After passing through a series of electrical resistance-type heaters the air was allowed to pass through a stilling tank to allow equilibration of air temperature and was then exhausted vertically upward through a cylindrical nozzle. A maximum jet temperature of 750°F could be produced. Both jet mass flow rate and heater power were infinitely variable allowing varying jet configurations. Nozzle diameters of 3/4" and 1" were used. In order to minimize the effects of "stray" convection currents on the laser beam the heaters and stilling tank were surrounded by an insulated housing. The air-space between the heaters and stilling tank and the housing was ventilated with ambient air and exhausted a distance from the jet.

A three-dimensional actuator, mounted directly above the jet nozzle, was used for locating the transducers within the jet. Motion is allowed along a vertical axis as well as two perpendicular horizontal axes.

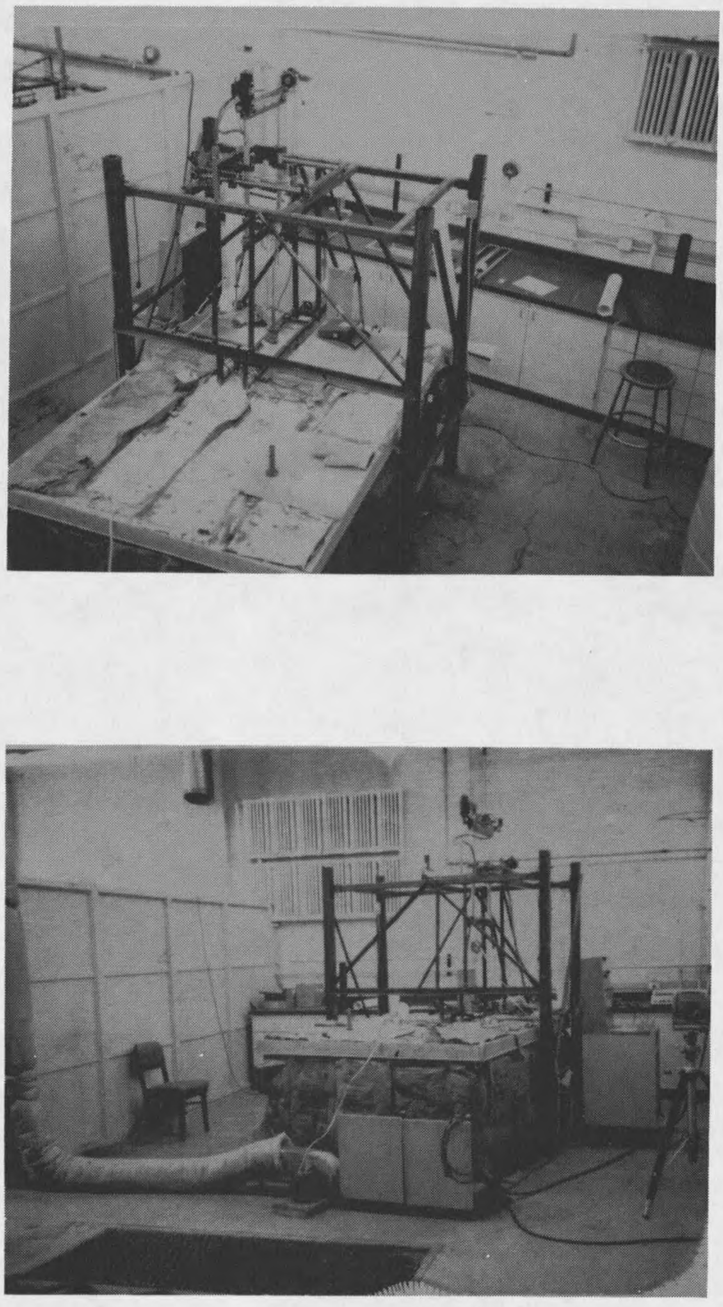

Figure 1. Jet apparatus

Actuator positioning was controlled from a remote station located near the jet.

An accurate orifice-type flowmeter provided jet-mass flow measurement.

Optical Apparatus

An optical system consisting of a laser, a means of directing the beam through the jet, and an intensity detector apparatus to determine the distribution of intensity within the beam after passing through the jet was constructed. A 35 mW Spectra Physics helium neon laser (wavelength = 632.8 nm) was used as a source of light. In order to direct the beam through the jet a system of four mirrors was constructed as illustrated in Figure 2. The positioning of the mirrors was adjustable, thereby allowing the beam to intersect the jet at varying heights above the nozzle as well as at points off the axis of the jet. Coarse mirror positioning was performed by remote control from a control station located near the jet facility. "Fine-tuning" of the mirror alignment was accomplished by adjustment screws located on the mounting bracket of each mirror. After passing through the mirror system (and jet) the beam was directed at the intensity detector apparatus, approximately 32 feet away.

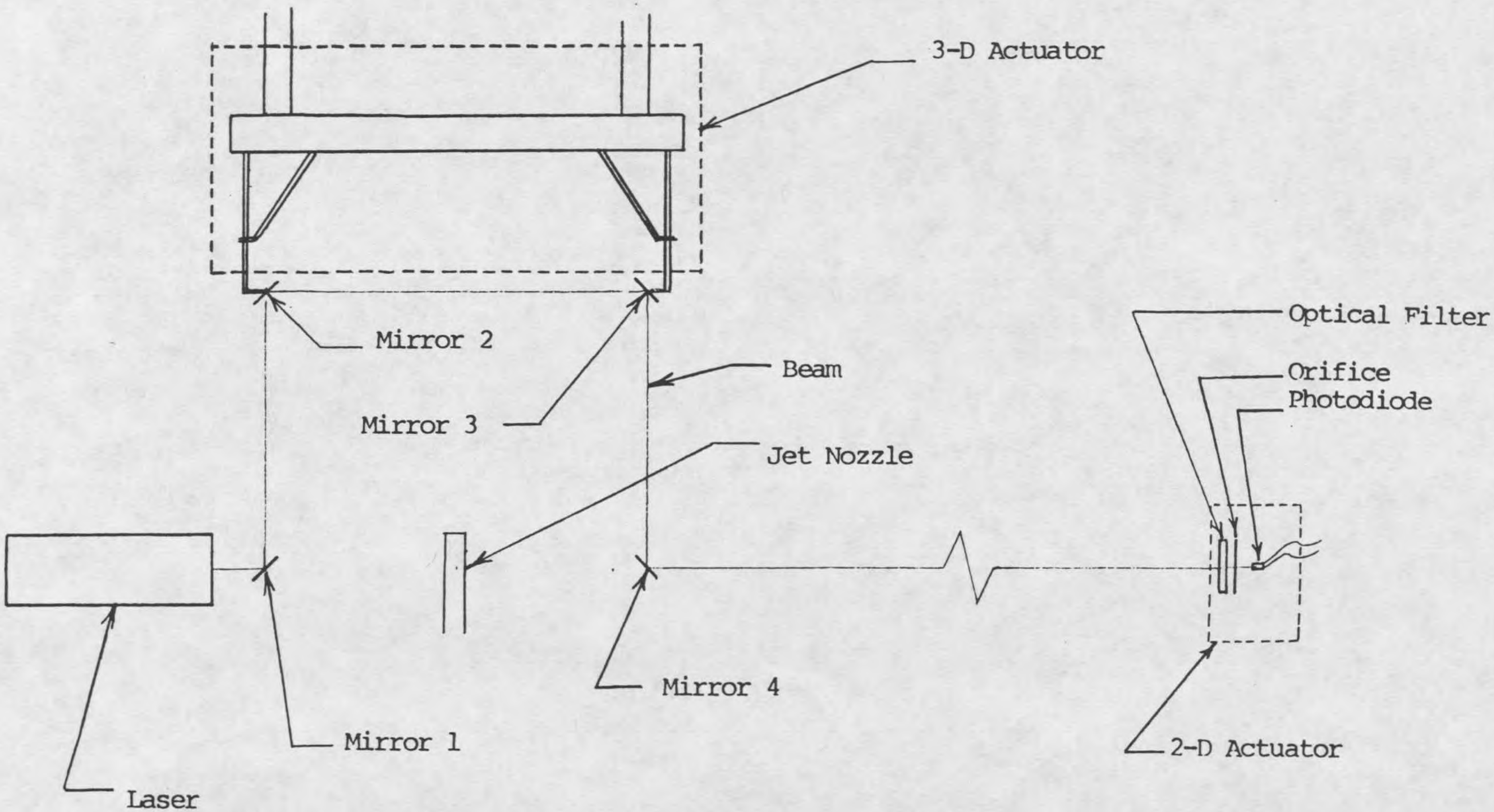

Figure 2. Optical system

Beam shielding was used between the mirror system and the detector in order to minimize the effects of random room currents on the beam. The detector assembly consisted of an optical bandpass filter, an orifice for increased resolution of measurement, and a photodiode for detection of light intensity. The detector assembly is discussed in detail on page 23. The detector assembly was mounted on a two-dimensional actuator, allowing the beam cross-section to be traversed along both horizontal and vertical axes. The output of the detector/actuator assembly consisted of a voltage proportional to intensity incident on the detector as well as actuator position voltage outputs proportional to the photodiode position along the horizontal and vertical axes. The voltage output from the photodiode was recorded using mean voltage (Fluke 8600A Digital Multimeter, Hewlett Packard Model 412A) and root-mean-square voltage (Hewlett Packard 3400A, TSI Model 1076 variable time constant) instruments in order to obtain both mean and fluctuating intensity data at each data point location. Since beam intensity distributions were determined by moving a single intensity detector to different points within the beam cross-section, the distributions obtained were time-averaged as opposed to being instantaneous "snapshots" of the entire beam cross-section at a particular instant in time.