

Conference Paper
Optical Sensors
Rio Grande, Puerto Rico United States
July 14-17, 2013
ISBN: 978-1-55752-981-7
Laser Based Sensors II (SW4B)

Optoelectronic Sensor on Moving Platforms for Monitoring Environmental Parameters

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http://dx.doi.org/10.1364/SENSORS.2013.SW4B.4

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Abstract

The development of an optoelectronic sensor for real time monitoring of environmental parameters in atmosphere and ocean is presented here with envisaged applications onboard automobiles, aircrafts and underwater platforms.

OCIS Codes
(120.0120) Instrumentation, measurement, and metrology : Instrumentation, measurement, and metrology
(010.0280) Atmospheric and oceanic optics : Remote sensing and sensors

Citation
R. Tatavarti, A. Pachiyappan, A. Jakkam, S. Rao S, and A. Tatavarti, "Optoelectronic Sensor on Moving Platforms for Monitoring Environmental Parameters," in *Advanced Photonics 2013*, K. Ewing and M. Ferreira, eds., OSA Technical Digest (online) (Optical Society of America, 2013), paper SW4B.4.
http://www.opticsinfobase.org/abstract.cfm?URI=Sensors-2013-SW4B.4

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OPTOELECTRONIC SENSOR FOR MOVING PLATFORMS

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ABSTRACT

The design and development details of an optoelectronic sensor for real time monitoring of velocity, temperature and density of stratified fluids (atmosphere and ocean) are presented, with envisaged applications onboard automobiles, aircrafts and underwater platforms.

Index Terms — Optoelectronics, Sensor, Fluid, Monitoring, Moving Platforms.

1. INTRODUCTION

The need for a highly sensitive non-intrusive sensor for monitoring stratified fluids in the real world from moving platforms like aircrafts in the atmosphere or submerged bodies in the ocean was the impetus for this work. Recent research focuses on the use of optical scattering as a promising mechanism for fluid monitoring [1-4]. Although these are very promising and many important defense industries are working towards perfecting the technologies involved, and developing highly sensitive aircraft based systems, these involve accurate optical accessories and alignments and precision engineering for yielding good results in real time. Most of the going efforts also necessitate huge costs and complex optical configurations where in substantial space needs to be allocated for the systems onboard aircrafts [5, 6]. As is well known space for scientific systems on board aircrafts especially defense aircrafts, is always a premium. Against this background we attempted to look at the utility of the concept of forward scattering of light for monitoring fluids in stratified fluids like the atmosphere, and ocean.

2. NON INVASIVE OPTOELECTRONIC SENSOR FOR MONITORING SURROUNDING FLUIDS

The optoelectronic system for real time monitoring of stratified fluids (for example atmosphere and oceans) comprises of a continuous wave, coherent, collimated beam of light (or a laser) falling on the surface of a photo detector in such a way that the received light falls partially on the active sensing area of the photo detector and partially on the encapsulation of the photo detector, after passing through the stratified fluid medium (Figure 1). The light intensity falling on the photo detector undergoes changes due to changes in the optical refractive gradient generated as a result of fluid motions in the stratified fluid. The photo detector records the precise time varying light intensity pattern, corresponding to the time varying motions experienced in the stratified fluid due to motions. The output signals from the photo detector are recorded and compared with those obtained from a standard sensor. The efficacy of this method and system for real time monitoring of stratified fluids was demonstrated.

The relationship between the optional refractive index and the temperature (density) of a fluid is given by the Gladstone-Dale Equation, $(n-1)=\kappa\rho$; *i.e.,* $n=1+\kappa\rho$ (the optical refractive index is linearly related to fluid density) where, n is the optical refractive index, ρ the density of the fluid and κ is a constant coefficient which is a function of the laser wavelength and the fluid characteristics. Therefore, the refractive index gradient is linearly related to temperature (density) gradient or the change in refractive index gradient will yield the change in density gradient of a fluid (see Figure 2). Based on this concept, it can be inferred as follows, as suggested by Tatavarti *et al.* [7]:

$$\varepsilon_x = \int \frac{1}{n}\frac{\partial n}{\partial x} dz$$

$$\delta_x = \frac{L}{n}\frac{\partial n}{\partial x} \approx \frac{L}{\rho}\frac{\partial \rho}{\partial x}$$

$$\varepsilon_y = \int \frac{1}{n}\frac{\partial n}{\partial y} dz$$

$$\delta_y = \frac{L}{n}\frac{\partial n}{\partial y} \approx \frac{L}{\rho}\frac{\partial \rho}{\partial y}$$

where, L is the optical path length of the beam in fluid and x and y are horizontal and vertical co-ordinates. The dimensions of δ_y are m/ (Kg/m^3) × (Kg/m^3)/m. Therefore, δ_y will be dimensionless.

For the optoelectronic systems the minimum resolvable δ (an artefact of the sensitivity of the position sensing detector used), *say*, 0.1µm = 1×10^{-7}m; an optical path length L designed as, *say*, 0.1m; ∂y = 1 m; and an average density value of ρ (air) ≈ 1Kg/m^3. For calculating the minimum resolvable $\Delta\rho$ (Δ T) we have

$$\frac{\delta_y \rho}{L} = \frac{\partial \rho}{\partial y}$$

i.e., the minimum resolvable $\Delta\rho$ is, O (10^{-6}) Kg/m^3 (or the minimum resolvable temperature is 0.001ºC).

Hence, the sensitivity and accuracy of the optoelectronic sensor system for monitoring fluid parameters using the concept of forward light scattering, are extremely good (orders of magnitude higher) compared to conventional existing technologies, and the same can be realized, with position sensing detectors of sub-micron accuracy and sensitivity.

It is well documented [8] that changes in the environment in which a light beam is traversing can be realistically monitored with increased sensitivity (compared to conventional sensing mechanisms) if one could study the optical diffraction and interference fringes which are manifest. However, to observe these fringes one needs to make elaborate design involving complex optical configurations and precise optical alignments. Santhanakrishnan and Tatavarti [9] have patented a simpler method to simultaneously generate and detect the diffraction fringes caused due to changes in the environment, and the same is used in this study. Therefore, in order to further increase the sensitivity and the dynamic range of sensing we have focused the laser beam in such a way that the light falls partially on the active sensing area of the detector, and partially on the outer perimeter of the active sensing area of the photo detector, thus ensuring a spatial intensity pattern on the photo detector [9].

3. EXPERIMENTAL INVESTIGATIONS

Light from a laser diode modulates due to the changes in fluid velocity and temperature, following the principle of Laser beam deflection and forward scattering of light. The modulated light signals are allowed to fall on the edge of the photo detector, thus ensuring generation of diffraction fringes due to interference between the direct light on the active sensing area and the diffracted light from the edge of the photo detector. The photo detector used is a position sensing photo diode which converts the light energy into electrical energy and gives the light intensity and position on the detector. The signals from the photodiode are processed using a simple algorithm on board a computer which yields information regarding the fluid velocity and temperature. Experiments were conducted with a small fan capable of blowing air at three speeds (7cm/s, 10.5cm/s, 12.6cm/s); and an warm air blower (hair dryer) capable of blowing warm air at constant speed of 0.5m/s with different temperature settings of 40ºC, 60ºC and 80ºC. The speeds of the fan and the temperatures of the air blower were measured using standard procedures and instruments. The experiments were conducted with different configurations to monitor the effect of blowing air at different speeds at room temperature, and blowing air at constant velocity with different temperatures. The geometry and speeds of the air emanating from both the Fan and the hair dryer were different. During the experiments the laser source and the photo detector were separated by 0.5m, while the Fan/Warm Air Blower were located about 2cm, perpendicularly facing the laser beam.

The laboratory setup during the experiments for demonstrating the mechanism of the sensor is pictured in Figure 3. A diode laser of 5mW of 635 nm was used as the source of light. A 2-D position sensing silicon photo diode with a positional resolution of 0.1µm was used as the photo detector. The light beam from the laser diode was made to fall on the edge of the photo detector, with the beam falling partially on the active sensing area and partially on the outer perimeter of the photo detector. This ensured a higher signal to noise ratio and a high dynamic range during detection as was earlier demonstrated [9] The geometry of the 2D position sensing photo detector vis-à-vis the position of the fan and the warm air blower (hair dryer) is shown in Figure 4. The air flow was towards the negative x-direction of the photo detector. The y-direction is considered positive upwards.

Observations were recorded by connecting a data acquisition system to the 2-D position sensing photo detector and selecting a data sampling rate of 16Hz, and quantizing the signals with 16 bit resolution. Data were observed during different phases with various air speeds at ambient temperature and with different temperatures at constant air speed. The output from the photo detector is obtained in terms of the beam deflections in microns from the reference origin in the x and y directions during different experimental phases (δ_x, δ_y) .

3. RESULTS AND DISCUSSION

Figure 5 shows the time averaged (1-sec) data clusters of x and y deflections (δ_x, δ_y) of the laser beam due to various air speeds generated by the fan at room temperature. Figure 6 show the time averaged (1-sec) data clusters of x and y

deflections (δ_x, δ_y) of the laser beam due to various temperatures generated by the air blower at constant air speed. The linear regression plots and the corresponding relations between (δ_x, δ_y) are also shown in the figures. Centroids of each of the data cluster corresponding to various phases of the experimental observations (changing air speeds and temperatures) were determined using the K-Means method and depicted as squares (grey in color) in the Figures 5 and 6. Based on the observed data clusters, regression equations and the computed centroids a simple signal processing algorithm, whose flow chart is shown in Figure 7, determines the fluid velocity and temperature. The derived equations for determining the fluid velocity and temperature are as follows:

$$T = -0.023672d^2 + 1.9592d + 40 \quad (^{o}\mathrm{C})$$

$$u = -0.416731d^2 + 4.592204d - 0.021443 \quad \mathbf{(cm/s)}$$

where, $d = \left(\delta_{x_i} - \delta_{x_0}\right)^2 + \left(\delta_{y_i} - \delta_{y_0}\right)^2$,

$\delta_{x_i}, \delta_{y_i}$ are the instantaneous values

$\delta_{x_0}, \delta_{y_0}$ are the reference values

Our experimental investigations demonstrated that the sensitivity and accuracy of the results are very good (more than 3 orders of magnitude higher) compared to conventional standard intrusive sensors.

4. CONCLUSIONS

A non-invasive and highly sensitive optoelectronic technique for the design and development of a sensor for mobile platforms for real time monitoring of surrounding fluid velocity, temperature (density) which can be adapted for use on board moving aircrafts or underwater platforms like ROVs, torpedoes, ships and submarines is demonstrated.

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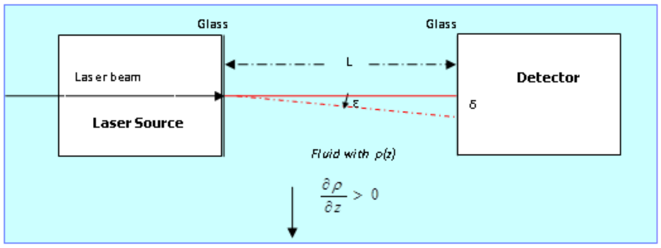

Figure 1: Laser beam deflection in a density stratified fluid

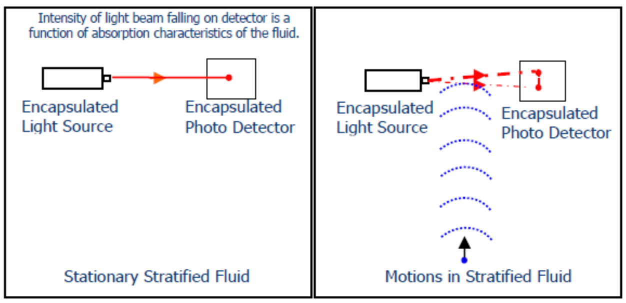

Figure 2: Schematic description of the working principle of optoelectronic system for monitoring stratified fluid motions.

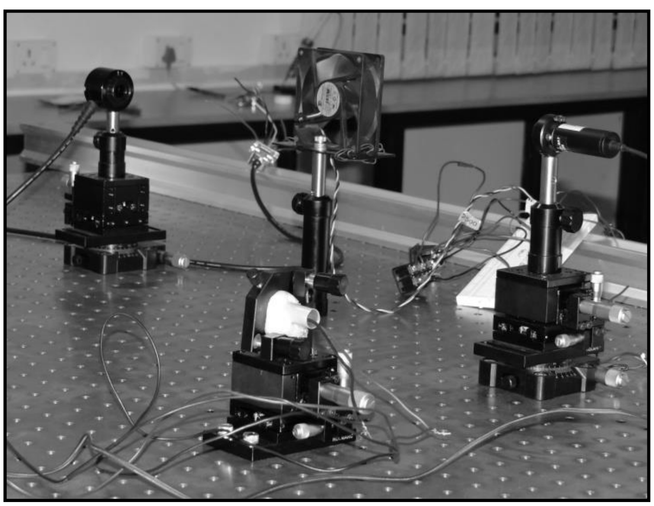

Figure 3: Laboratory setup for demonstration of the proposed system.

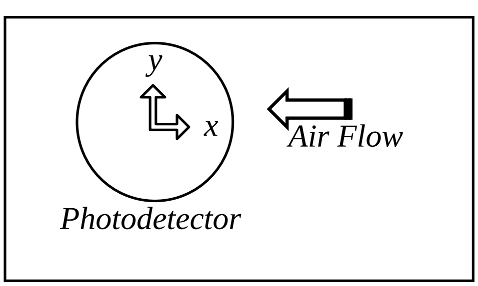

Figure 4: Geometry of the photo detector vis-à-vis the air flow direction from fan / blower

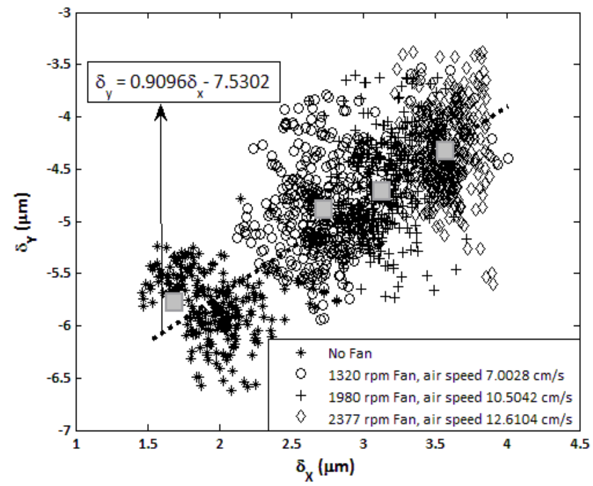

Figure 5: Observed data cluster of (δ_x, δ_y), for different air speeds.

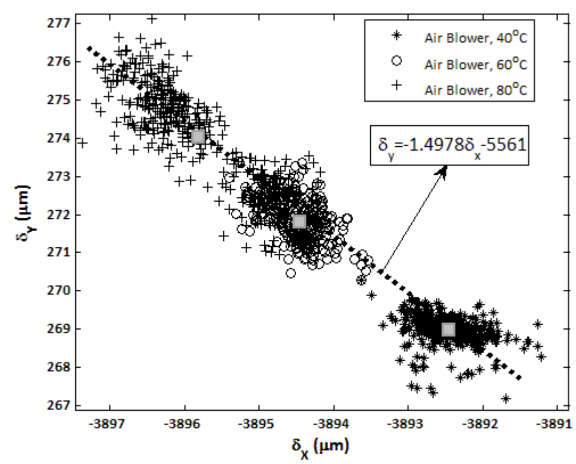

Figure 6: Observed data cluster of (δ_x, δ_y), for different temperatures.

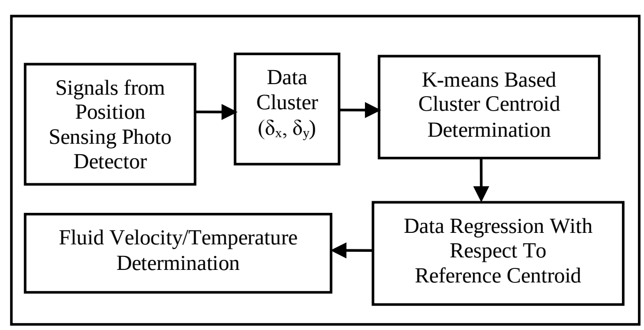

Figure 7: Block diagram of the signal processing algorithm for determination of fluid velocity and temperature (density).