Presented at the COMSOL Conference 2009 Milan

COMSOL CONFERENCE 2009

OCTOBER 14-16 2009, MILAN, ITALY

A Study of Laser Doppler Anemometer Using COMSOL Multiphysics

Ion LANCRANJAN*

Camelia GAVRILA **

*Advanced Study Centre - National Institute for Aerospace Research “Elie Carafoli, Bucharest, Romania
http://www.incas.ro

**Technical University of Civil Engineering Bucharest
http://www.utcb.ro

Outline

1. Introduction
2. Theory
3. Results and Discussion
4. Conclusions
5. References

INTRODUCTION

- In this paper, we propose a study of a laser Doppler Anemometer using COMSOL Multiphysics. This study is under development. The main purpose consists in replacing Pitot tube anemometer.
- The Doppler Effect using laser as radiation source has important applications for design and building anemometers (LDA) used for in-flight air speed measurements. The air speed measurements are vital for safe flights.

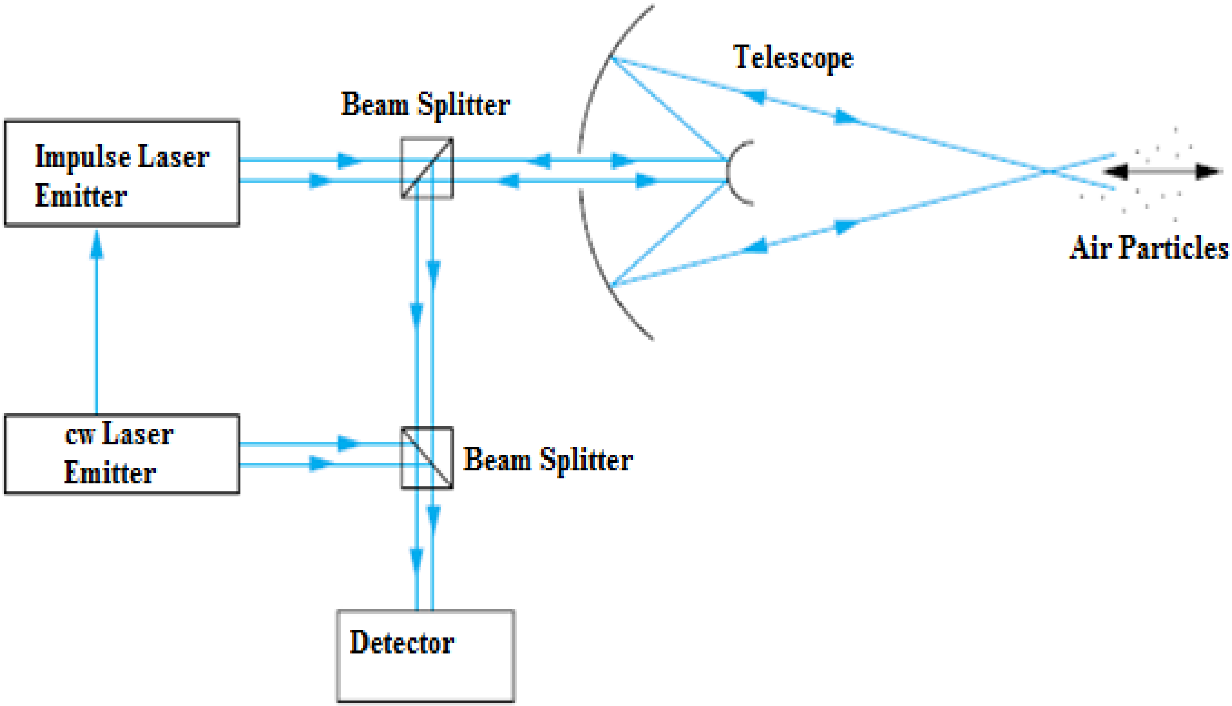
INTRODUCTION

- The main basic idea of Doppler techniques consists in measuring the frequency of scattered light from a moving particle thereby altering the frequency of the incident laser signal.
- This altered frequency of light can be determined directly with frequency-dependent optical processing using a spectrometer or an optical filter by converting light frequency changes into light intensity fluctuations using interference of light.

THEORY

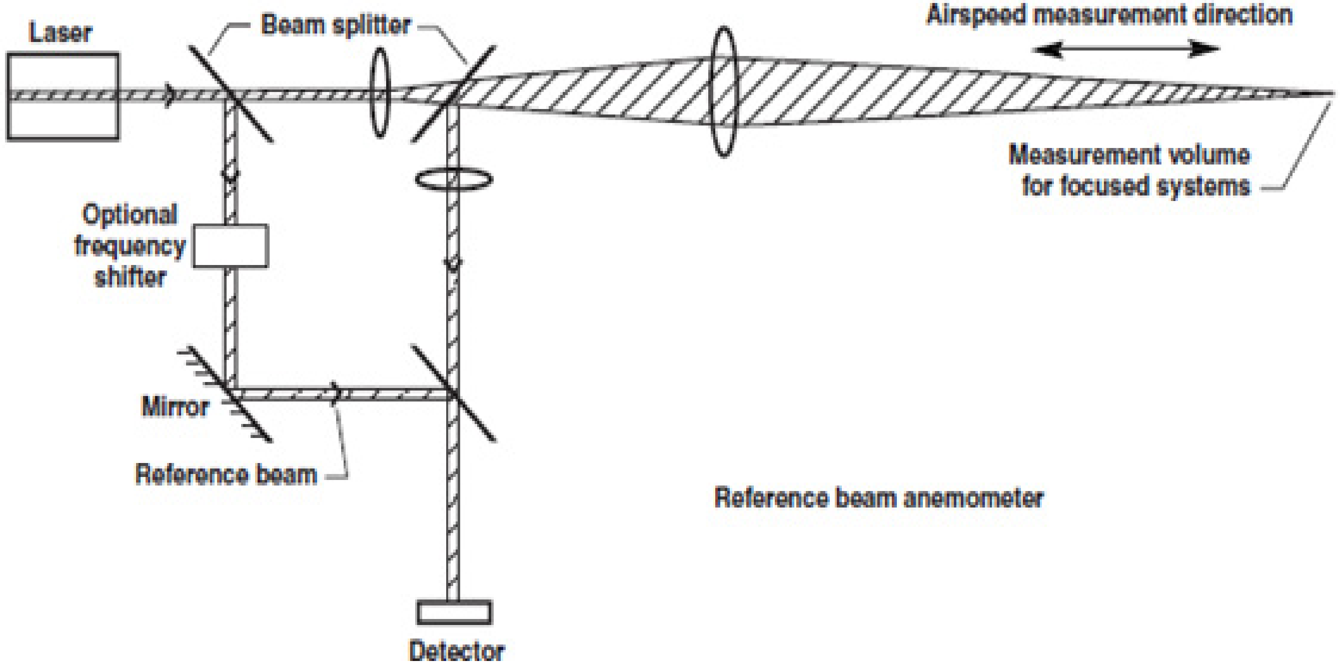
- The schematic of two experimental LDA setups are presented in the following figures. It is worth to be pointed that these are schematic of common LDA which are in use, onboard on flying air-planes.
- Both examples of LDA setup schematic have as a common detail the fact that laser radiation is focused at some distance from the airplane into a volume of flowing air.

THEORY



Example of LDA setup schematic.

THEORY



Example of LDA setup schematic.

THEORY

The Doppler effect was observed for the first time by the physicist Christian Doppler. It consists in the followings:

- A moving radiation source, a time variable signal source generates a signal of frequency ν and wavelength λ.
- A stationary observer will measure a frequency ν_m for the signal emitted by the moving radiation source, different of ν.

THEORY

The measured signal frequency, ν_m is defined as:

$$\nu_m = \nu + \Delta\nu$$

$\Delta\nu$ is the frequency shift measuring the magnitude of Doppler Effect.

In the case of a LDA, the radiation emitter and detector are in the same geometrical position, location. This means that frequency shift is doubled, as defined by the equation:

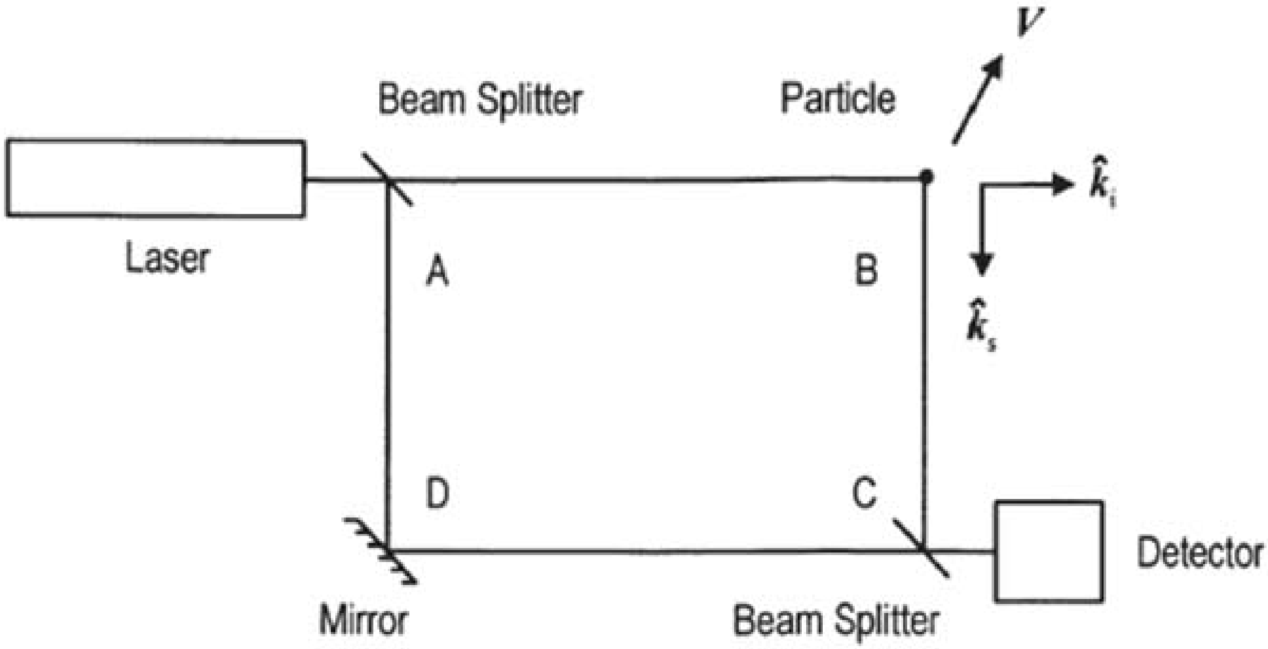
$$\Delta\nu = \frac{2v}{\lambda}$$

V denotes the speed of flowing air particles.

THEORY

The common approach for LDA devices consists in using a detection system based on converting light frequency changes into light intensity fluctuations using interference of light. The altered frequency of laser light scattered by particles of flowing air can be determined directly with frequency-dependent optical processing, i.e., by using a spectrometer or an optical filter. Practically, this means the use of an interferometer setup like the one presented in Figure – a Mach-Zehnder interferometer.

THEORY



Setup of a Mach-Zehnder interferometer – Laser Doppler Anemometer configuration

THEORY

The starting point of this frequency shift measuring setup consists in considering the light scattered by a single particle denoted by the subscript *m.* A proportion of this light propagates around the path ABC to form the object arm of the interferometer and is received at the detector. If the wave-length and frequency of the illuminating laser are λ and v , respectively, the complex amplitude, U_m, incident on the detector due to this component can be written in the form

THEORY

U_m, the laser light complex amplitude incident on the detector can be written in the form:

$$U_m = A_m e^{\left[j 2\pi \left(vt - \frac{x}{\lambda} \right) \right]}$$

x -path length. A_m -amplitude of the scattered radiation at the detector.

If the particle is moving with constant velocity, V, for small excursions from this basic geometry the path length can be written in the form:

$$x = x_0 - n\left(\vec{K}_s - \vec{K}_i\right) \cdot \vec{V}t$$

$\vec{K}_s$ unit vectors in the directions of the illuminating and scattering directions. n is the refractive index of the flowing medium. x_0 is a constant.

Electromagnetics & Optics III

THEORY

The detected signal complex amplitude is:

$$U_m = A_m e^{\left[j2\pi \left(vt - \frac{n(\vec{K}_s - \vec{K}_i)\cdot\vec{V}t}{\lambda} \right) \right] - \frac{x_0}{\lambda}}$$

An additional term is added to the frequency of the scattered light - the Doppler shift, Δ*v:*

$$\Delta v = \frac{n(\vec{K}_s - \vec{K}_i)\cdot\vec{V}t}{\lambda}$$

The reference beam propagates around the path ADC and the complex amplitude, U_R, of this beam at the detector can be written as:

$$U_R = A_R e^{\left[j2\pi \left(vt - \frac{x_R}{\lambda} \right) \right]}$$

$\phi_m = \frac{2\pi(x_R - x_0)}{\lambda}$

THEORY

The signal output measured by the detector is proportional to the incident intensity, *I,* which can be written as:

$$I = A_m^2 + A_R^2 + 2A_m A_R \cos\left(2\pi\Delta\nu t + \phi_m\right)$$

The phase constant, φ_m, is given by: $\phi_m = \frac{2\pi(x_R - x_0)}{\lambda}$

All in-flight optical air flow velocity measurements use light scattering. Light is scattered on in-homogeneities in the optical refractive index of a medium from both air molecules and aerosols en-trained in the air.

Results and Discussion

The COMSOL Multiphysics program is used to simulate the propagation of laser beam inside a focusing volume. The variations of observed laser signal frequency induced by the scattering on the flowing air particles is considered.

The procedure was the following: we select 3D as the Space Dimension, then in the list of Physical Models the following menu link COMSOL Multiphysics>PDEModes>ClassicalPDEs>PDE,General Form

Results and Discussion

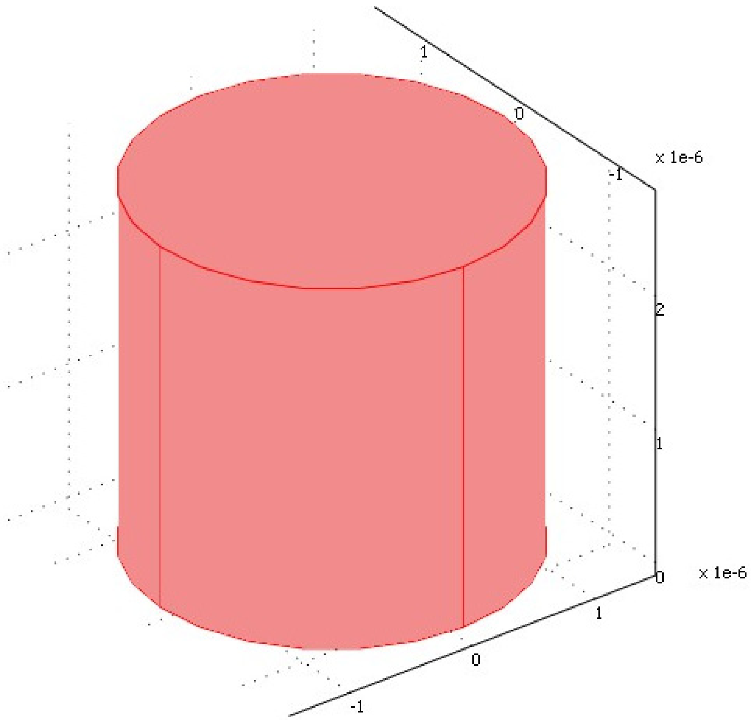
The parameters of the laser light – air particles interaction volume were defined using the following equations:

$$w_0 = \frac{4\lambda r}{\pi D} \qquad \Delta L = \frac{s \cdot \lambda \cdot r^2}{\pi \cdot D^2}$$

w_0 -beam waist diameter; *r* -light beam focusing distance; *D* - lens or telescope input aperture diameter.

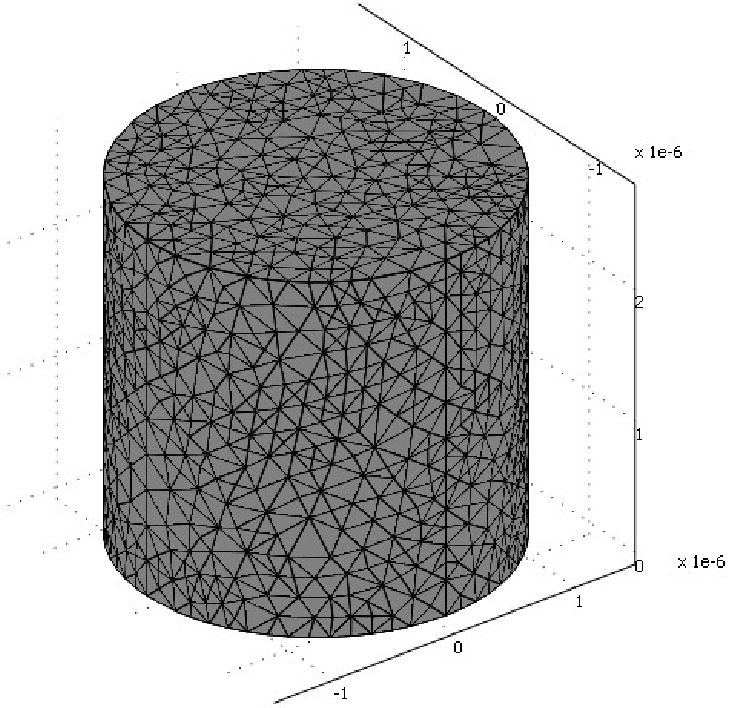
The case of using a solid state Nd:YAG laser was considered-emission wavelength of 1.064 μm. The transverse laser intensity beam distribution was approximated as Gaussian with an waist of ~45 mm at a distance of 150 m from the laser emitter. The estimated values of w_0 and DL were of 10^{-5} m as order of magnitude.

Results and Discussion



Geometry of the LDA interaction focusing volume for λ = 1.06 μm incident wavelength.

Results and Discussion



Geometry of the LDA interaction focusing volume for λ = 1.06 μm incident wavelength. The COMSOL mesh grid can be observed.

Conclusions

- In this paper we have demonstrated the versatility of COMSOL Multiphysics regarding the modeling and simulation of in-flight laser Doppler anemometer based on use of Doppler effect and Fabry - Perot etalon composed of Bragg grating reflectors.
- The obtained COMSOL Multiphysics models are under development for fulfillment of aeronautic industry design needs. The considered development includes comparison with experimental results.

References

[1] SMART (A.). – Optical velocity Sensor for Air Data Application, Optical engineering, vol.31, 1, 1992.

[2] WOODFIELD (A. A.) et VAUGHAN (J. M.). –Using an Airborne CO2 CW Laser for Stream Airspeed and Windshear Measurements, TM FSB 557, 1964.

[3] MANDLE (J.). – Apport de l'anémométrie laser à la sécurité aérienne, L'Aéronautique et l'Astro-nautique, janvier 1987.

[4] MANDLE (J.). – A Laser Anemometer Reference for Air Data Calibration, NAECON, Dayton Ohio, 1988.

[5] WERNER (C.), KÖPP (F.) et BISELLI (E.). - Measurements of the Wind Profile over Sea. Proceeding of the 3rd Topical Meeting on Coherent Laser Radar, juillet 1985.

[6] DESTARAC (G.), CATTIN-VALSECCHI (F.),LOPEZ (C.) et MANDLE (J.). – Apport de l'Anémométrie laser aux essais en vol A 330/A 340. Symposium ETTC Arcachon, 1993.

References

[7] MANDLE (J.). – FLAME: Future Laser Atmo-spheric Measurement Equipment, Aerodays 93, Naples, octobre 1993.

[8] F. Durst, A. Melling, J. H. Whitelaw: Principles and Practice of Laser Doppler Anemometry, Academic, New York (1976).

[9] B. Hiller, R. K. Hanson: Simultaneous Planar Measurements of Velocity and Pressure Fields in Gas Flows using Laser Induced Fluorescence, Appl. Opt. 27, 33 (1988)

COMSOL CONFERENCE 2009

OCTOBER 14-16 2009, MILAN, ITALY

Thank You!

Ion LANCRANJAN* J_J_F_L@yahoo.com

Camelia GAVRILA ** cgavrila2003@yahoo.com

**Technical University
of Civil Engineering Bucharest
http://www.utcb.ro

*Advanced Study Centre - National Institute
for Aerospace Research “Elie Carafoli,
Bucharest, Romania
http://www.incas.ro