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Optimization of laser Doppler system for velocity measurement

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In the study of the atmosphere, one main task is not to influence the phenomena. This can be done by using optical methods. One of these optical methods is laser Doppler. One application that can benefit from the advantages of laser Doppler method is to determine the velocity of atmospheric flow around aircrafts. The objective of this paper is to study the influence of a laser Doppler system on the process of velocity measurements and on the measurement precision in order to optimize the system for the use in atmospheric applications. The theoretical aspects were used to simulate the phenomena and the simulations were compared with experimental determination of velocities around and aerodynamic profile using laser Doppler method. The optimization of laser Doppler systems used in atmospheric applications is necessary because if the velocity is more precisely measured than the collected environmental data can be correctly calibrated.

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Keywords: laser, laser Doppler method, velocity measurement

1. Introduction

The mains advantages of using optical methods (laser Doppler) in atmospheric studies and flow measurements are the precision and the fact that it doesn't influence the phenomena.

One of the most spectacular applications of Doppler optical phenomena is the determination of stars and galaxies speed by measuring the phase shift of the received light [1]. These measurements are easy because the stars are sources of electromagnetic radiation and the relative phase shift is proportional with the ratio between the speed of the object and the speed of light [1].

The velocity measurement at ground and in the terrestrial atmosphere are more difficult because the objects doesn't emit electromagnetic radiation in the spectral domain of interest (the object most be illuminated) and phase shift between the emitted and the received radiation most be measured [1].

Other important applications of the laser Doppler method are: velocity and vibrations measurement in mechanical mechanisms, transports, industrial production, aeronautical industry, atmospheric movements, wind study and atmospheric turbulences, study of aerosols, etc. [1, 2].

Comparing with applications involving objects, the use of Doppler effect in atmospheric measurements presents some technical difficulties because of the weak reflected signal which most be analyzed for wavelength [1].

Another application of the laser Doppler effect is to measure the speed of the air flow. As a particularity, it is also used to determine the speed of aircrafts instead of using the tubes Pitot, which is more convenient for military aircrafts because it reduces the radar signature. Another advantage of laser Doppler systems use for aircrafts is that it can measure the air flow speed at different distances from the aircraft [3].

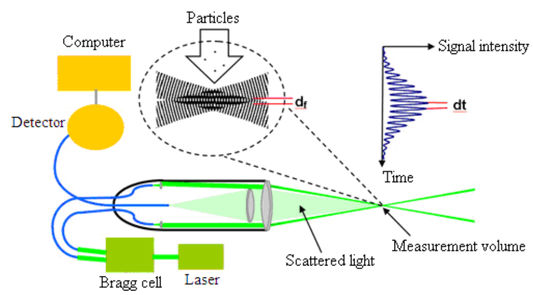


Fig. 1. Laser Doppler system [4]

Generally, a laser Doppler system has the fallowing components:
- light source (laser);
- Bragg cell which induces a phase shift that helps to determine the direction of the particle movement;
- beam splitter;
- emitter and detector head;
- light detector;
- signal processor.

The aim of this research is to study and to optimize laser Doppler systems used for the study of the atmosphere and for the measurement of air flows around an aerodynamic profile. In order to optimize the laser Doppler system, the interdependence of the system characteristics was studied and used to simulate the phenomena, simulations which were compared with experimental measurements of the flow around and aerodynamic profile.

2. Laser Doppler system characteristics

The laser Doppler method uses the laser beams as source of monochromatic light. The interference of two laser beams forms a bright grid of fringes which has a great contrast. In order to obtain the diffraction models, the beams most be coherent, and have the same intensity and polarity. More, for the detection of scattered light, the laser beams intensity most be great enough.

2.1 The distance between the interference fringes

The distance between the interference fringes (Δx) is dependent with the laser beams wavelength and the half angle between the two beams [5]:

$$\Delta x = \frac{\lambda}{2\sin\frac{\theta}{2}} \tag{1}$$

where: λ - laser beams wavelength;
θ - half angle between the two beams.

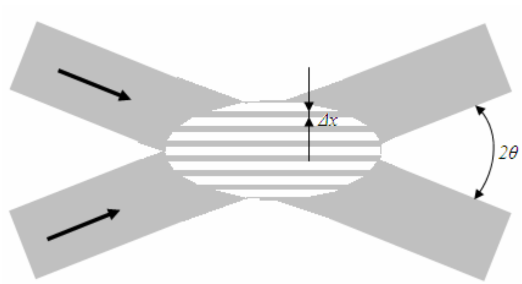


Fig. 2. The interference fringes

2.2 The dimensions of the measurement volume

The measurement volume resulting at the intersection of two laser beams of a laser Doppler system is an ellipsoid. In order to determine the dimensions of the ellipsoid, the fallowing equations are used [5]:

$$x = \frac{r_w}{\cos\frac{\theta}{2}} \qquad y = r_w \qquad z = \frac{r_w}{\sin\frac{\theta}{2}} \tag{2}$$

where:
-*x, y, z* are the semi-dimensions of the ellipsoid as presented below.
-r_w is the laser beam waist. Usually, the laser beam waist is located at the intersection of the two beams.

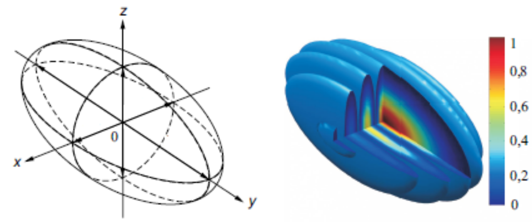


Fig. 3. The semi-dimensions of the ellipsoid [6]

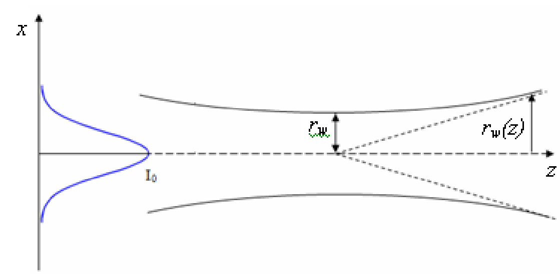


Fig. 4. Laser beam waist [7]

2.3 Number of interference fringes

The number of interference fringes depends on the measurement volume and the distance between the fringes. The number of interference fringes is defined by the fallowing relation [5]:

$$N_{fr} = \frac{2x}{\Delta x} \tag{3}$$

2.4 Frequency difference on the detector

The frequency difference on the detector can be calculated using the fallowing relation [5]:

$$f_D = \frac{2\sin\frac{\theta}{2}}{\lambda} v_x \tag{4}$$

where v_x represents the component of the velocity parallel with the measurement direction.

2.5 Detection volume

The dimensions of the detection volume are given by the fallowing equations [5]:

$$x_d = x\sqrt{\frac{1}{2}\ln\left(\frac{I_{r\max}}{I_d}\right)} \qquad y_d = y\sqrt{\frac{1}{2}\ln\left(\frac{I_{r\max}}{I_d}\right)} \qquad z_d = z\sqrt{\frac{1}{2}\ln\left(\frac{I_{r\max}}{I_d}\right)} \tag{5}$$

where: I_d – minimum detectable intensity;
I_{rmax} – maximum reflected intensity.

2.6 Velocity measurement sensitivity

The velocity measurement sensitivity [6, 8, 9] is defined by the fallowing equation:

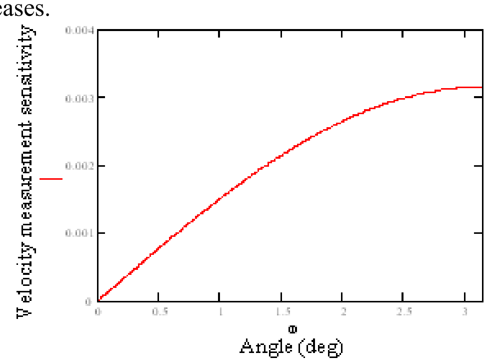
$$D = \frac{1}{\Delta x} \tag{6}$$

where, Δx is the distance between the interference fringes.
So, the frequency difference on the detector becomes:

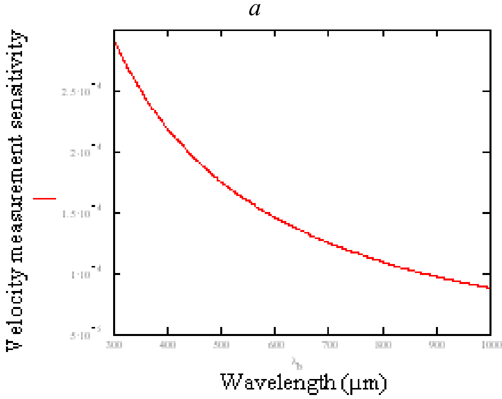
$$f_D = \frac{v}{\Delta x} = Dv \tag{7}$$

where, v is the particle's velocity.

In order to analyze the relation between the velocity measurement sensitivity with the angle between the two beams and with the wavelength of the laser beam, the equations from above were included in a Mathcad code.
Analyzing the graphs presented in Fig. 5, we can conclude that the velocity measurement sensitivity of a laser Doppler system increases with the angle between the two laser beams (figure *5.a*) and the velocity measurement sensitivity decreases if the wavelength of the laser beam increases.



a



b

Fig. 5. The relationship between the velocity measurement sensitivity and the angle between the two beams (a) and the wavelength of the laser beams (b)

2.7 The Doppler signal of the velocity

In order to analyze the Doppler signal of the velocity we make the assumption that the profile of the laser beams is Gaussian.

The light reflected by a particle passing through the measurement volume is received by a detector, thus, resulting a Doppler signal proportional with the intensity of the light incident on the detector. The Doppler signal caused by a single particle passing through the measurement volume is dependent with the position of the particle in the measurement volume.

The laser signal can be written as fallows [6]:

$$s(t) = A(t)\left[M + \cos\phi(t)\right] \tag{8}$$

where: t is the time.
M indicates the presence of a low frequency component. M depends on the difference in intensity between the two convergent laser beams. If the two laser beams have the same intensity, M=1.

$$A(t) = Ke^{\left[-\left(\frac{x(t)}{c/2}\right)^2 - \left(\frac{y(t)}{b/2}\right)^2 - \left(\frac{z(t)}{a/2}\right)^2\right]} \tag{9}$$

represents the amplitude of the laser signal. *x(t)*, *y(t)* and *z(t)* are the position of the particle inside the measurement volume. *a, b* and *c* are the dimensions of the measurement volume on the three axes. *K* is a coefficient dependent by the laser power, the electronically amplification, the viewing direction and the efficiency of light scattering.
The instantaneous signal phase is:

$$\phi(t) = 2\pi D z(t) + \phi_0 \tag{10}$$

where: D - velocity measurement sensitivity;
ϕ_0 - initial phase of doppler signal.

In order to determine the sign of the velocity it is necessary to introduce the frequency of the Bragg cell, f_B [6, 8, 9]. Thus, if the intensity of the two laser beams is the same, the Doppler signal becomes:

$$s(t) = Ke^{(-\beta v_z (t-t_0))^2}\left[1 + \cos\left(2\pi f_B t + 2\pi D v_z (t - t_0) + \phi_0\right)\right] \tag{11}$$

where:
t_0 is the moment when the particle passes though the center of the measurement volume;

$$\beta = \frac{2}{a}$$

$$2\pi D v_z (t - t_0) = 2\pi f_D t$$

3. Numerical determination of laser Doppler system characteristics

The theoretical aspects presented before where integrated in Matlab in order to determine and optimize the parameters of a laser Doppler velocity measurement system. The Matlab code determines and optimizes the parameters of a laser Doppler system which uses a Gaussian laser beam.

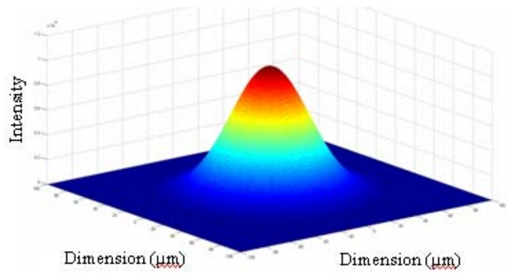
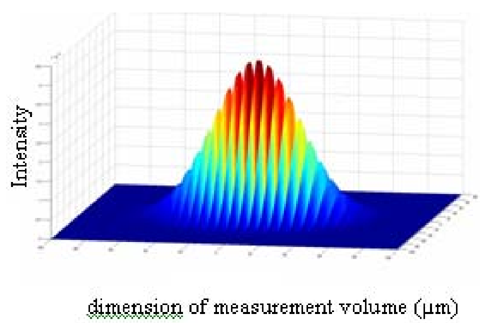


Fig. 6. The profile of Gaussian laser beam

The Matlab code computes the fallowing characteristics of the laser Doppler system:
a. distance between interference fringes;
b. dimensions of the measurement volume;
c. number of interference fringes;
d. velocity measurement sensitivity;
e. intensity of interference fringes;



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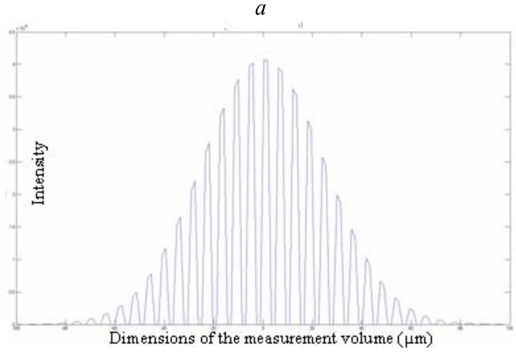
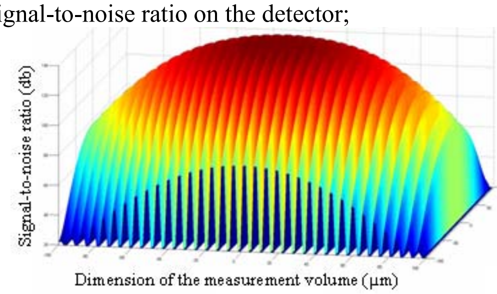


b

Fig. 6. The intensity of interference fringes, 3D (a) and 2D in the center of the measurement volume (b)

f. light scattered by a particle;
g. light intensity on the detector;
h. light power on the detector;
i. signal-to-noise ratio on the detector;



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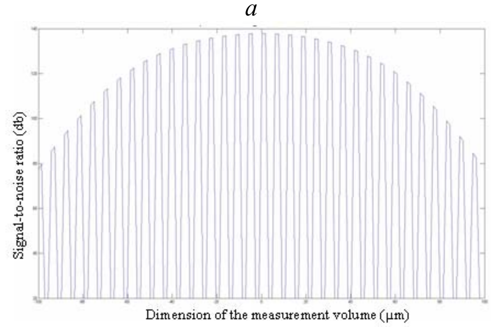

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Fig. 7. The signal-to-noise ratio on the detector, 3D (a) and 2D in the center of the measurement volume (b)

j. Doppler signal.

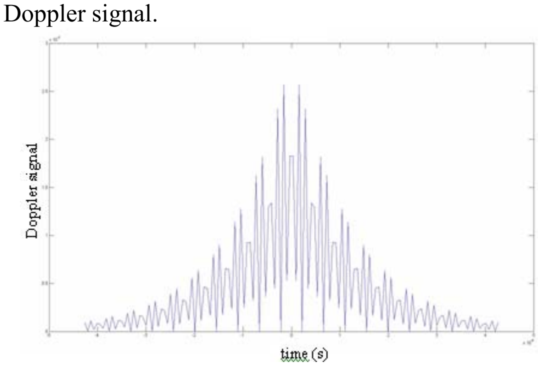


Fig. 8. Doppler signal

4. Validation of the theoretical results through experimental determination of the velocities around an aerodynamic profile using laser Doppler method

In order to validate the theoretical results, there were made experimental measurements around an aerodynamic profile using laser Doppler method. The experimental measurements were made around a biplane configuration and in order to have a better idea of the phenomena, the measurements were made for different relative position of the aerodynamic profiles of the biplane configuration.

4.1 The model used in the experimental measurements

The model used in the experimental measurements is a biplane configuration consisting from two naca0012 aerodynamic profiles with different relative position to each other.

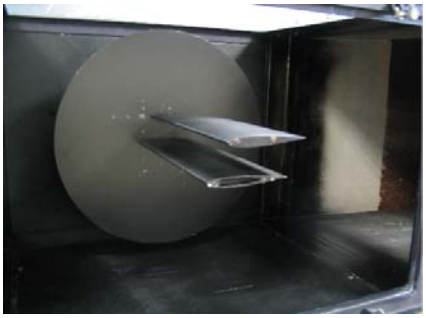


Fig. 9. The biplane configuration

4.2 Measuring equipments

The laser Doppler systems used to determine the velocities around the model is presented in the image below.

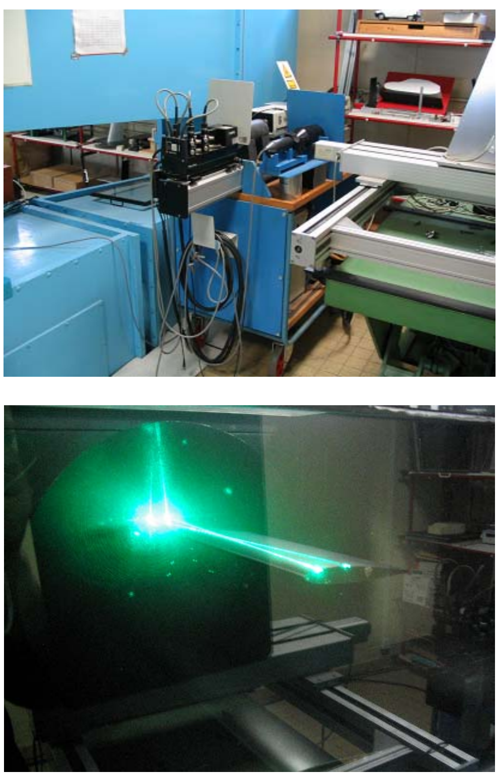


Fig. 10. The laser Doppler system

The measurements were made in a transversal plane located in the middle of the model, in predefined points.

4.3 Determination of laser Doppler characteristics using the Matlab code

The laser Doppler characteristics are:
- the distance between the interference fringes;
- total number of interference fringes;
- the dimensions of the measuring volume;
- Doppler frequency;
- measurement precision.

The characteristics of laser beam emitted by the system are:
- wavelength: 514,5 nm;
- power: 4 mW;
- diameter: 1 mm.

The calculated parameters of the laser Doppler system are:

Table 1. Laser Doppler parameters

Characteristic	Value
Distance between the interference fringe	Δx=2,9516 μm.
Dimensions of the measurement volume	x = 501.9099 μm y = 500 μm y = 5736,9 μm
Number of interference fringe	N_{fr}=340
Doppler frequency	f_D = 6,776 MHz.
Velocity measurement sensitivity	D = 0,3388

The intensity of the interference fringe

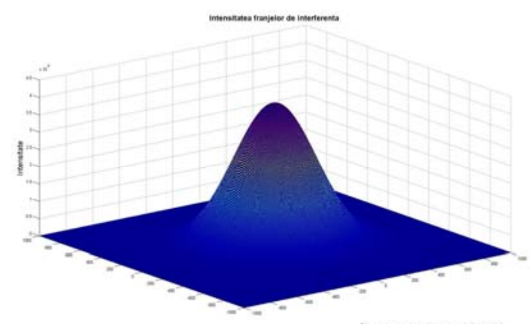


Fig. 11. The calculated intensity of the interference fringes.

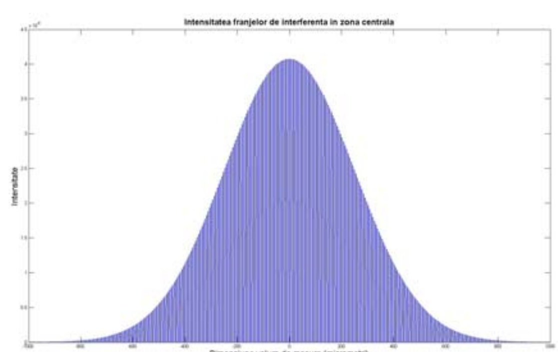


Fig. 12. The calculated intensity of the interference fringes in the middle of the measurement volume

Detector's signal-to-noise ratio

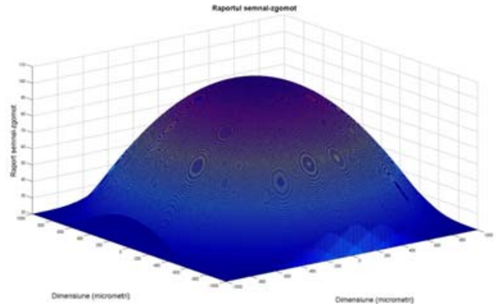


Fig. 13. Detector's signal-to-noise ratio

Doppler signal

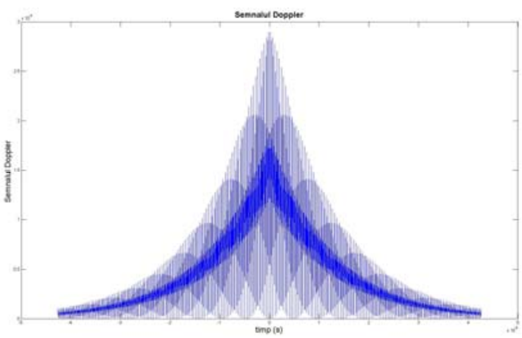
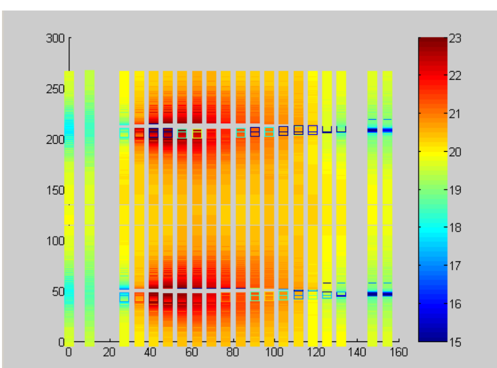
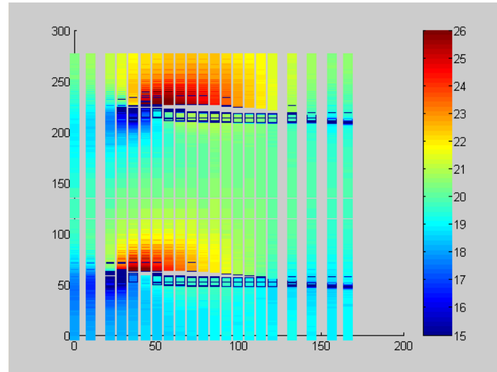


Fig. 14. The Doppler signal resulted when a particle is passing through the middle of the measurement volume

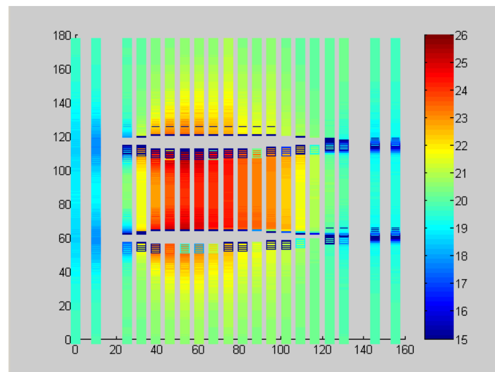
4.4 The measured velocities field around the aerodynamic model



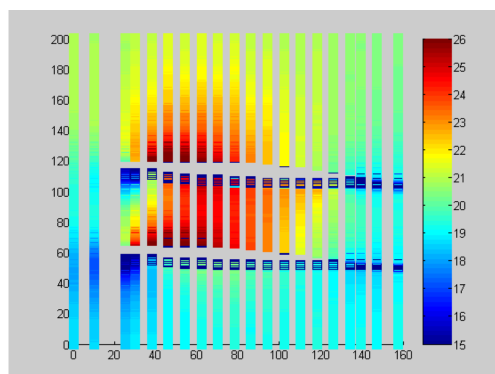
Configuration 1



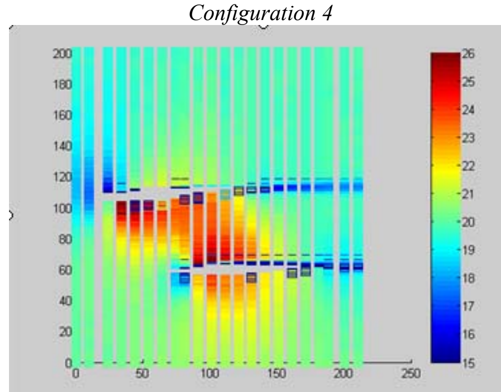
Configuration 2



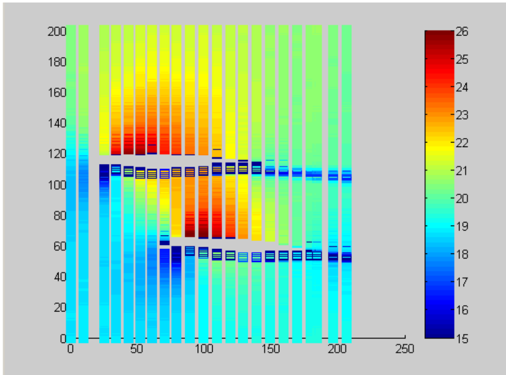
Configuration 3



Configuration 4



Configuration 5



Configuration 6

Fig. 15. The measured velocities field around the aerodynamic biplane model (configurations 1-6)

In order to determine the velocity of the air flow in a single point of the configuration, 1024 measurements were made and the velocity in that point was considered to be the average value of the measurements.

Based on multiple measurements in each point of the configuration, also, the measurements errors were determined. The measurement error was found to be small compared to the measured velocity (approx. 0,1-0,2 m/s for a average velocity of approx. 20-24 m/s). Greater values for the measurement error were founded in those points where the configuration of the biplane model influenced the velocity measurements. The vibration of the biplane model caused by the airflow interrupted the laser beam in the close vicinity of the biplane model, thus resulting grater measurements errors.

5. Conclusions

The laser Doppler method is non-intrusive and the measurement precision is about the wavelength of the laser beam if the system is optimized.

Considering all advantages, the laser Doppler method is ideal for the measurement of the air flow around an aircraft, determining in this way the speed or the aircraft without influencing the it's aerodynamic characteristics.

The paper presents the theoretical aspects regarding the optimization of a laser Doppler system in order to increase its measuring precision for a certain application and working conditions. Also, in order to validate the theoretical aspects, there were made experimental measurements to determine the velocity fields for the airflow around an aerodynamic model taking into account the measurements errors.

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