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Preliminary Application of a DGV System Using a Single Intensified Camera in a Supersonic Wind Tunnel

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Abstract : A DGV system using a continuous wave Argon laser and an optical arrangement with a single intensified camera has been set up at the ISL blow-down supersonic wind tunnel. The first tests have been performed over a 12.5° 2D wedge at a freestream Mach number of 2. A mean velocity field has been calculated from 28 individual measurements. When compared to the theoretical velocity distribution, deviations of 8 % to 15 % have been obtained. Preliminary tests have also been performed on a missile-like model equipped with a lateral jet system. Individual as well as mean velocity fields are presented.

Keywords : Doppler global velocimetry, Supersonic flow, Wind tunnel, Wedge, Side jet.

1. Introduction

Doppler Global Velocimetry (DGV) is a method dedicated to the measurement of velocity fields of moving objects or flows and is based on the optical frequency shift of the light scattered by the moving object illuminated by a laser beam.

The principles of Doppler Global Velocimetry are based on the fundamental concept introduced by Komine, 1991, i.e. employing a molecular/atomic absorption filter to determine the frequency shift of the scattered light. After this first publication, several experimental systems based on a cw laser and on a pulsed laser have been developed (e.g., McKenzie, 1996). In most cases, an optical system with two cameras has been used.

Almost all experimental DGV systems have been validated on a rotating disc set-up (see for example Wernert et al., 2003) or on jet flows, in the latter case, by comparison with another measuring system, Laser Doppler Anemometry (LDA) or Particle Image Velocimetry (PIV). DGV has been applied to different types of flows: for example, airfoils, turbomachinery and boundary layers. Elliott and Beutner (1999) and Elliott (2001) provide comprehensive state-of-the-art reviews.

Concerning compressible flows, only a few publications can be found in the literature: some of these publications report measurements on supersonic jets (e.g. Clancy et al., 1998) and one concerns an airfoil in a transonic wind tunnel (Barricau et al., 2002). To our knowledge, only one publication has already reported DGV measurements in a supersonic wind tunnel (on a wedge and a delta wing): see Meyers (1996).

In the present paper, we present the first results concerning the use of our single camera DGV system in the ISL blow-down supersonic wind tunnel.

2. Principles of Doppler Global Velocimetry

As shown in Fig. 1, when an object is illuminated by a laser beam of frequency ν_0 propagating in direction $\vec{L}$, the Doppler shift $\Delta\nu$ of the light scattered by this object and collected by a detector (receiver) located along the direction $\vec{R}$ is expressed by:

$$\Delta\nu = \nu - \nu_0 = \frac{\nu_0}{c}\vec{V}(\vec{R} - \vec{L}) \quad (1)$$

where $\vec{V}$ is the velocity vector of the moving object. By using an absorption filter (iodine vapor cell), the Doppler shift is converted into intensity variations on the detector. Hence, if the detector is replaced by a CCD camera, an image is obtained where the greyscale value of each pixel is a function (through the Doppler shift) of the velocity component $V_m = \vec{V}(\vec{R} - \vec{L})$ of the corresponding point of the object (see Fig. 1). In order to remove the greyscale value variations which are not due to the Doppler shift, several images are required: a signal image (obtained through the iodine cell), a reference image (obtained without iodine cell) and some correction images (Wernert et al., 2003).

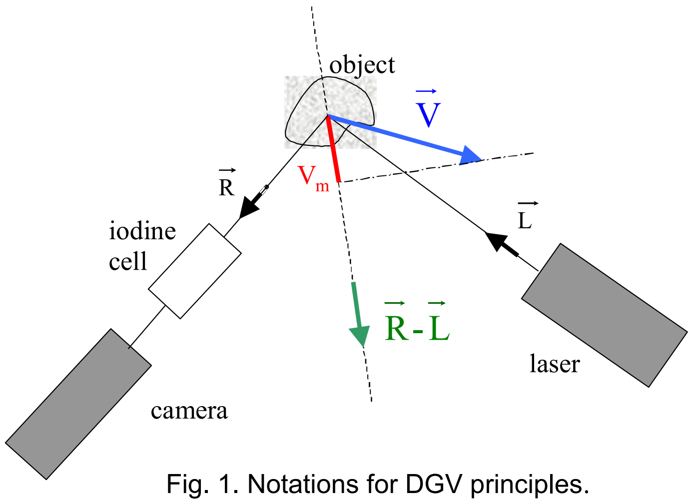

Fig. 1. Notations for DGV principles.

The principles of Doppler Global Velocimetry are summarized in Fig. 2: the velocity distribution on the object generates successively Doppler shift of the laser light, transmission variations in the iodine cell and greyscale value variations on the CCD camera. When measurements are realized, the greyscale values are first recorded on the camera and the velocity field has to be calculated by following the reverse way. Details of these calculations (including image processing procedures) are given in Wernert et al. (2003).

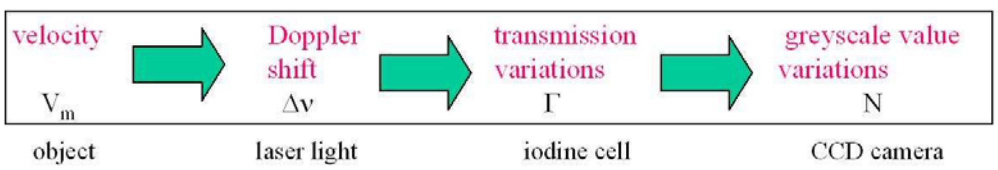

Fig. 2. Principles of DGV.

3. Experimental Set-Up

3.1 DGV System

The experimental DGV set-up developed at ISL contains the following main elements (Wernert et al., 2003):

- a cw Argon laser ("Spectra Physics Beamlok" model 2085-20S) operating at a wavelength of 514.5 nm with 7 W nominal single-line power and frequency stabilization systems (Spectra Physics "J-Lok" and "Z-Lok" devices).
- an iodine cell developed at DLR Köln, Germany as detailed in Roehle (1999), (Fig. 3). This cell is operated at a temperature of about 65°C – 70°C and comprises a temperature control system. Figure 4 shows the normalized transmission curve of the iodine cell.
- an optical set-up containing the CCD camera. Most existing DGV set-ups use 2 cameras. For economy's sake, our goal was to use only one camera to take the two kinds of images needed in DGV (signal image through the iodine cell and reference image). As shown in Fig. 5, signal and reference images are obtained simultaneously by adjusting properly beamsplitters and mirrors (details are given in Wernert et al., 2003). As the mean concentration of seeding particles was not high enough in the wind tunnel to allow the use of a non-intensified camera with small recording times, an intensified 12 bit PCO Dicam Pro camera with 1280 (H) ×1024 (V) pixels was chosen.
- a laser frequency monitoring system is also used to set the laser frequency at the desired working point on the iodine cell transmission curve.

Fig. 3. View of the iodine cell.

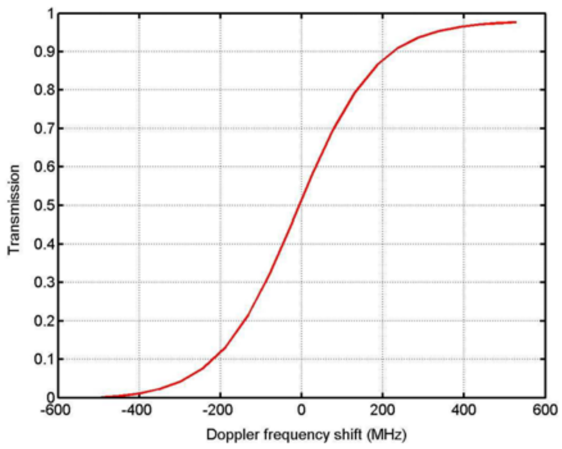

Fig. 4. Normalized transmission curve of the iodine cell.

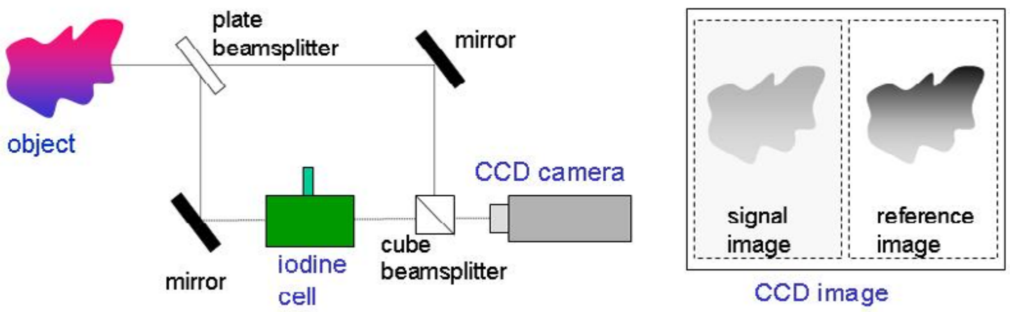

Fig. 5. Optical set-up and recorded image on the CCD camera.

3.2 Supersonic Wind Tunnel Arrangement

The ISL blow-down supersonic wind tunnel has a test section of size 20 cm x 20 cm and is able to produce freestream flows from Mach number 1.4 to 4.4. The preliminary tests reported in the present paper have been conducted in the configuration shown in Fig. 6:

- vertical laser sheet placed in the model longitudinal plane of symmetry.
- camera located perpendicular to the laser sheet.

Seeding is accomplished by using ISL manufactured devices, based on the Laskin nebulizer principle (Schäfer et al. 2001). Similar to other velocimetry techniques like LDA and PIV, tracer particles seeding is a key issue in Doppler Global Velocimetry and also a difficult task in a supersonic wind tunnel because of the very high air flow rate (Wernert et al., 2004).

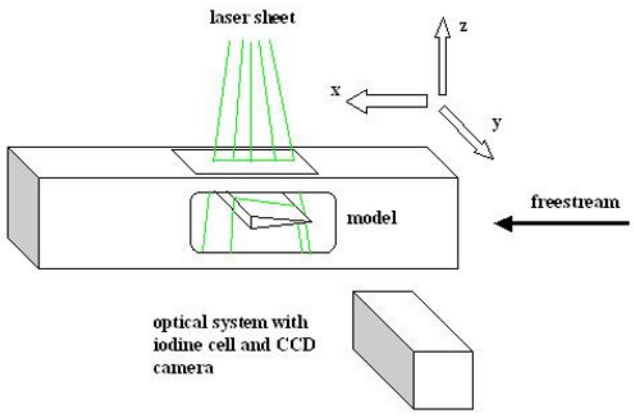

Fig. 6. Configuration for wind tunnel DGV experiments.

4. Preliminary Tests on a 2D Wedge

4.1 Measurement Conditions and Theoretical Flowfield

The DGV measurements on a 2D wedge were performed at the following conditions:

- freestream Mach number: $M_{1th} = 2$
- freestream velocity: $V_{1th} = 518$ m/s
- wedge half-angle: $\Delta = 12.5°$
- wedge at 0° incidence

By using the classical relations for oblique shocks (e.g. Anderson, 1990), we find the features of the theoretical flowfield over the wedge (Fig. 7):

- oblique shock angle: $\theta = 42°$
- Mach number downstream of the oblique shock: $M_{2th} = 1.56$
- velocity downstream of the oblique shock: $V_{2th} = 445$ m/s

Figure 8 shows a view of the calibration card image used to achieve an exact spatial correspondence between the reference and signal parts of the recorded images. The measurement area (in green) and the location of the theoretical oblique shock (in blue) are made visible. The size of the measuring area is 5.5 cm x 5.5 cm.

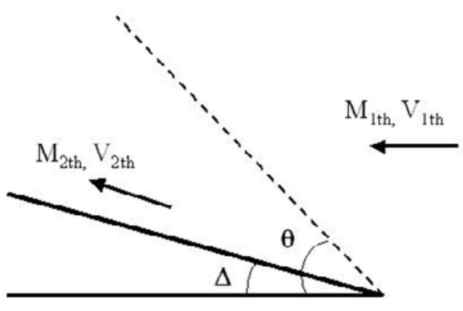

Fig. 7. Theoretical 2D flowfield over the wedge.

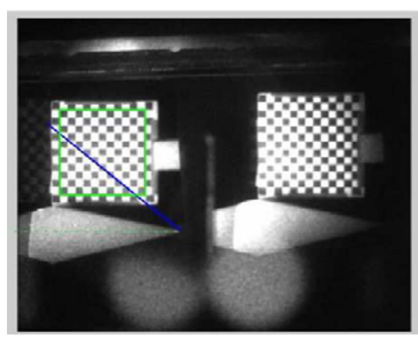

Fig. 8. Calibration card image: measuring area (in green) and location of the theoretical oblique shock (in blue) are shown.

The DGV images were recorded with the following settings of the CCD camera and laser:

- exposure time: 150 ms
- intensification rate: 65 %
- binning mode (2,2)
- laser working point corresponds to an iodine cell normalized transmission of 6 %.

4.2 Measured Velocity Field

The DGV measured velocity fields are seen to be very noisy (Wernert et al., 2004). This is mainly due to the noise introduced by the intensified camera. In order to attempt to remove this noise, a mean velocity field can be calculated from several raw velocity fields. This mean velocity field (Fig. 9) is obtained, for each pixel, by:

a) searching in all raw velocity fields the corresponding pixels having a normalized transmission value in an acceptable range (for example, 0.05 to 0.95).
b) calculating the arithmetic mean value of these pixels.
c) applying a 5,5-kernel median filter.

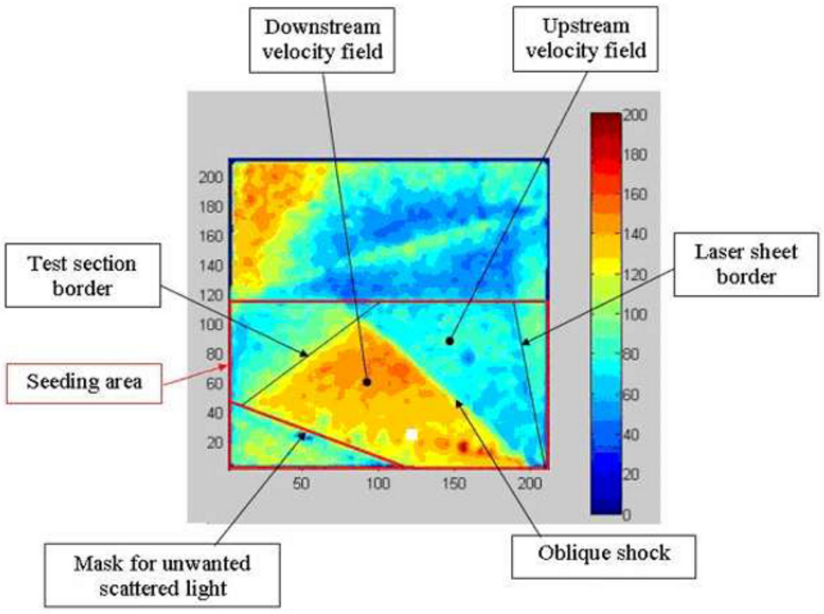

Fig. 9. Mean velocity field (in m/s) obtained from 28 DGV measured velocity fields.

4.3 Comparison between DGV Measured and Theoretical Velocity Fields

With the notations of Figs. 6 and 7, the theoretical velocity field over the wedge can be simply described with:

- upstream velocity field: $\vec{V}_{1th} = V_{1th}.\vec{x}$
- downstream velocity field: $\vec{V}_{2th} = V_{2th}.[\cos\Delta.\vec{x} + \sin\Delta.\vec{z}]$

By measuring the location points of the camera and the laser in the (x, y, z) frame of Fig. 6, the coordinates of the vector $\vec{R} - \vec{L}$ are calculated. If we neglect the divergence of the laser sheet (i.e. we assume the directions of vectors $\vec{R}$ and $\vec{L}$ to be constant for all points of the laser sheet), we find the following constant theoretical velocity components:

- upstream velocity field: $V_{m1th} = \vec{V}_{1th}.(\vec{R} - \vec{L}) = 87$ m/s
- downstream velocity field: $V_{m2th} = \vec{V}_{2th}.(\vec{R} - \vec{L}) = 170$ m/s

When calculating the DGV mean velocity components from Fig. 9, we find:
- upstream velocity field: $V_{m1} \cong 80$ m/s (deviation of 8% to the theoretical value V_{m1th})
- downstream velocity field: $V_{m2} \cong 145$ m/s (deviation of 15% to the theoretical value V_{m2th})

To our opinion, the measured deviations are mainly due to the noise introduced by the intensified camera and the low concentration of seeding particles which induce a poor signal to noise ratio on the recorded images. These points will be investigated in our next measurements by using new seeding devices and another camera.

5. Preliminary Tests on a Generic Side-jet Model

5.1 Measurement Conditions

The preliminary DGV measurements on a cone-cylinder-flare configuration equipped with a lateral jet system (Schäfer et al. 2001) were performed at the following conditions:
- freestream Mach number: $M_1 = 3$
- lateral jet exit Mach number: $M_{1jet} = 1.5$
- lateral jet reservoir pressure: 20 bars
- lateral jet reservoir temperature: 300 K

With these conditions, we get a static pressure ratio of 25 (jet exit static pressure divided by test section static pressure). Figure 10 shows a view of the side jet model mounted in the wind tunnel test section. The measuring area has a size of 7 cm x 7 cm.

The DGV images were recorded with the following settings of the CCD camera and laser:
- exposure time: 20 ms
- intensification rate: 65 %
- binning mode (2,2)
- laser working point corresponds to an iodine cell normalized transmission of 5 %.

When compared to the exposure time of 150 ms used for the measurements over the wedge (see section 4), the low exposure time of 20 ms can be explained by the much higher concentration of tracer particles obtained with the lateral jet seeding system.

5.2 Measured Velocity Field

By using the method outlined in section 4.3, a mean velocity field is obtained from 57 DGV measured velocity fields (Fig. 11). Figure 12 shows the final DGV velocity field scaled with the side jet model. More details are given in Wernert et al. (2004).

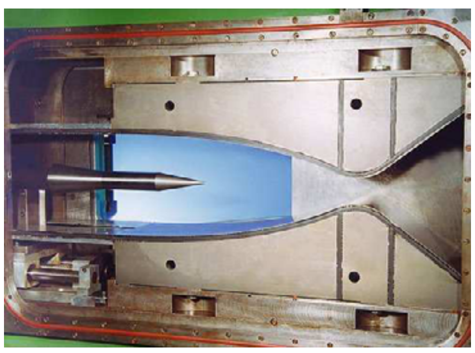

Fig. 10. Side jet model mounted in the wind tunnel test section.

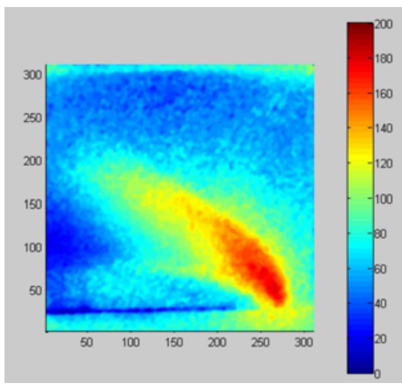

Fig. 11. Final velocity field (in m/s).

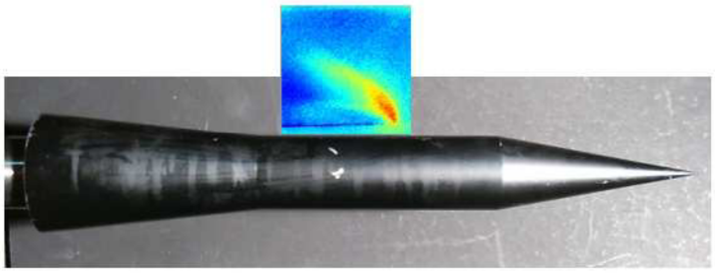

Fig. 12. Final DGV velocity field scaled with the side jet model.

6. Conclusion

A DGV system using a continuous wave Argon laser and an optical arrangement with a single intensified camera has been successfully set-up at the ISL blow-down supersonic wind tunnel.

The first tests, performed over a 2D wedge at a freestream Mach number of 2, have shown deviations of 8 % to 15 % over the theoretical velocity field. Preliminary tests have also been performed on a missile-like model equipped with a lateral jet system. Although these preliminary measurements were successful, many improvements remain to be done in the future. First of all, the concentration of tracer particles should be increased with new seeding devices. Then, all kinds of light reflections in the wind tunnel should be better masked and removed. Finally, some aspects of the image processing procedure should be improved. In the near future, new DGV measurements are planned in the ISL blow-down supersonic wind tunnel and the DGV velocity fields over the side jet model will be compared with CFD simulations.

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Author Profile

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Bastien Martinez: He studied aeronautics engineering at Ecole Nationale Superieure de Mechanique et d'Aerotechnique (ENSMA Poitiers in France) and received his Diplôme d'Ingénieur in 2000. He joined the French-German Research Institute of Saint-Louis (ISL) in 2001 and is now working on the development and application of Doppler Global Velocimetry to supersonic wind tunnels.