Free flight pressure sensitive paint measurements Mach 0.8

FREE FLIGHT PRESSURE SENSITIVE PAINT MEASUREMENTS MACH 0.8

T. Gauthier[c], B. Martinez, D. Klatt, S. Dobre, F. Saada, F. Leopold

French-German Research Institute of Saint-Louis, 68301 Saint-Louis, France

[c]Corresponding author: Tel.: +33(0)3895060; Fax: +33(0)3895048; Email: thibaut.gauthier@isl.eu

KEYWORDS:
Main subjects: pressure measurements, flow visualization
Fluid: transonic flows
Visualization method(s): Pressure Sensitive Paint
Other keywords: luminescence, free flight, combined measurement, space probe, CFD

ABSTRACT: *This article presents the new development of the Pressure Sensitive Paint (PSP) method for free flight measurements. The PSP technic is an optical, non-intrusive and provides major improvements in surface pressure investigations. Until now, PSP measurements are used into wind tunnel, especially for transonic and supersonic conditions with the model fixed into the test chamber. With the improvements of the method, we are able to produce measurements in real conditions of flight (temperature, pressure and motion). For this study, we used the sub-scale Earth re-entry space model at Mach 0.8 with no angle of attack to measure the base pressure. We used the TurboFib paint from ISSI which has a time response under 1 ms. According the Stern-Volmer equation, the intensity method is applied by measuring simultaneously with a dichroic filter the reference and the measurement image by two high-speed Photron camera SA-X. The PSP is excited by two continuous 12W LED lamps emitting at 405 nm and the luminescence signal is recorded at 650 nm. The goal of this study is to improve the PSP method for free-flight measurements, and compare results with PSP classic measurements in wind tunnel and pressure transducers measurements, to validate numerical CFD RANS computations.*

1 Introduction

In order to compare and validate the numerical simulation, experimental measurements are conducting into wind-tunnel. However, even if the Reynolds number is respected, forces, temperature, pressure and motion are studied by equivalence. Furthermore, in wind-tunnel, the model must be held by a fastening system, that limits the global understanding of the aerodynamic flow. With the improvements of the PSP technic, we are able to catch the pressure distribution in real conditions of flight. Indeed, the improvement of the paint time response and sensitivity, the quality of the high speed camera in terms of quantification (12 bits), sensitivity, CMOS sensor (20µm) and resolution, and also the post-processing development, allow to use of the PSP method for free flight measurements. In order to measure the base pressure of the model, we carried out comparative measurements between PSP free-flight, MPX pressure transducers and numerical RANS simulation.

2 PSP Principle

The Pressure Sensitive Paint (PSP) method is used to determine the entire surface pressure field in transonic and supersonic wind tunnel by a high-resolution camera [1]. This method, which is optical and non-intrusive, provides major improvements in surface pressure investigations. Each pixel recorded by the camera is converted into pressure information. The dynamic quenching effect and the luminescence are the two principal characteristics of the active molecule, the PtTFPP luminophore. With this molecular sensor, we obtained global measurements with a spatial resolution of a few micrometers for steady and unsteady flows. This method is particularly dedicated to study aerodynamics phenomena and complex structures, and to validate numerical simulation (turbulence model, meshes, boundary layer refinement) with the ANSYS CFX solver.

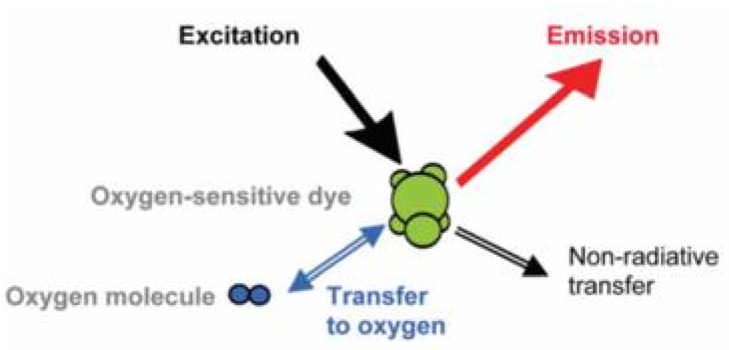


Fig. 1. PSP principle

The intensity method according to the Stern-Volmer equation is applied [2]:

$$\frac{I_{ref}}{I} = A + B\frac{P}{P_{ref}} \tag{1}$$

2.1 Fast response PSP

We used the TurboFIB from ISSI - a single luminophore which has a low time response under 1 ms and reduces temperature sensitivity (0.4% per °C). The paint is excited by a continuous water-cooling 12W LED lamp emitting at 405nm with a very stable illumination. The luminescence signal is recorded with a camera using a filter at 650nm.

A first layer of white paint is applied to increase the luminescence signal and to hide the eventual luminescence of the material composing the model. Then, the TurboFIB is applied by a spray-gun, and cured at 65°C during one hour in order to minimize the temperature sensitivity of the pressure response of the paint.

Fig. 2. High Intensity water cooled LED

3 Model configuration

3.1 Earth re-entry space model

This sub-scale Earth re-entry space model consists of a blunt forebody made of brass with a half-angle of 70° and a spherical nose, linked to the afterbody by a shoulder radius. The base geometry consists of a conical afterbody with half-angle of 47° ended by a radome. The reduced scale of the model was 1:30 compared to the real space configuration, resulting in a nominal model diameter of 80 mm with a length of 45.69 mm, for a weight of 507.7 g. To prevent gas leakages from passing between the sabot and petals at ignition that could destroy the PSP and the pressure transducers, a pusher plate located aft end of the sabot was used as seen in figure 3.

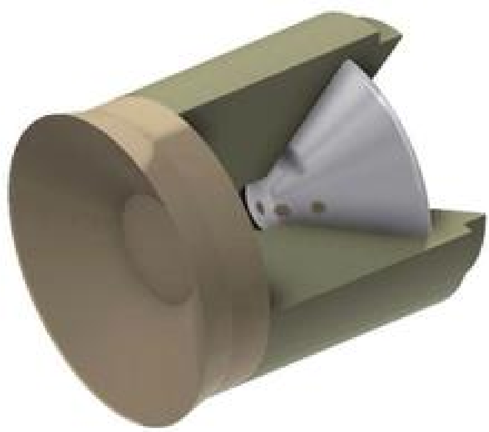


Fig. 3. Model sabot package

Fig. 4. Model with pressure transducers

The main electronic components equipping the model, consists of a 3D magnetic sensor, base pressure transducers, a power supply and a trigger system. Model instrumentation is based on 3 mains boards. The first one, 3D ACC/MAG, embeds a 3-axis MEMs accelerometer of ± 19 g full scale range and a 3-axis magnetometer based on anisotropic magneto-resistance (AMR) technology measuring Earth's magnetic fields in ±0.5 G range. The board supports the complete signal conditioning chain for the six axes to amplify and digitize analog signals [4].

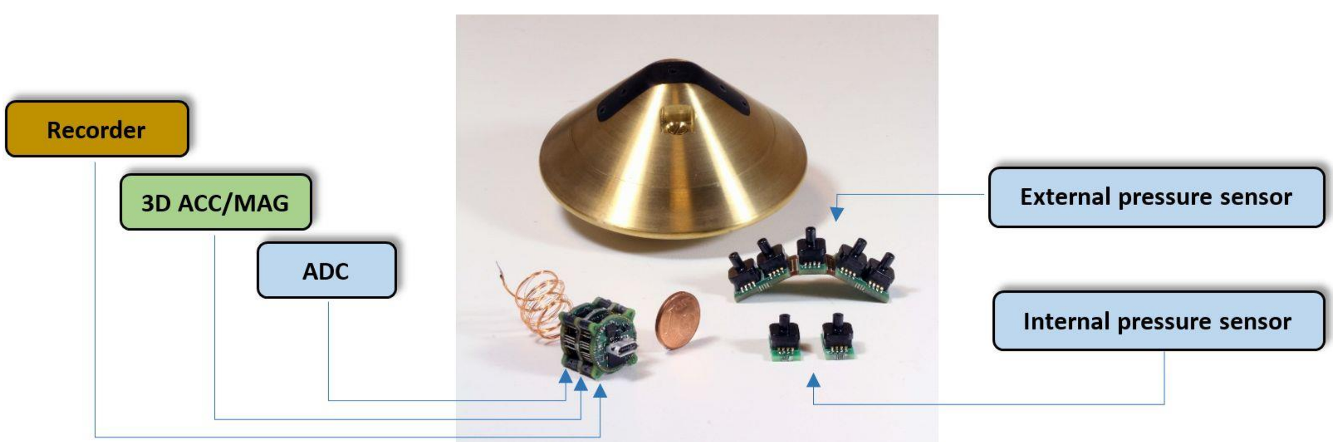


Fig. 5. Pressure sensor implementation

A second ADC board performs the analog to digital conversion of the 7 absolute pressure transducers MPXA6115A from Freescale Semiconductor Inc., conditioned voltage outputs giving measurement span between 15kPa and 115kPa. They are designed to support the gun launch acceleration up to 10’000 g. Mounted on a Flex PCB, 5 sensors are dedicated to external pressure measurement and 2 are integrated inside the probe in a sealed way to serve as a reference. The silicon pressure piezoresistive sensor is directly integrated on-chip with a temperature compensation [5].

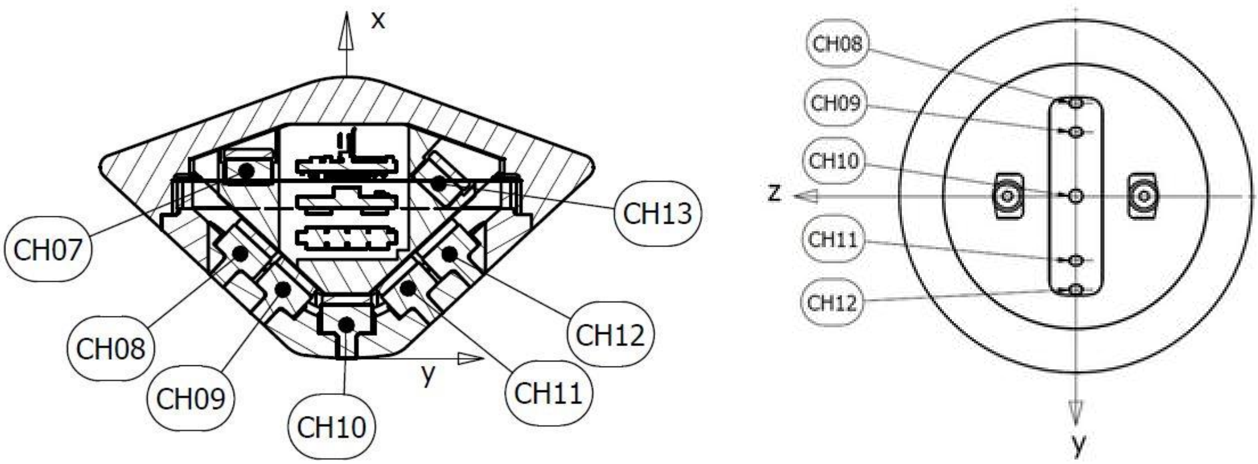


Fig. 6. Pressure transducers locations

Finally, the last board embeds the recorder system. It drives the sensor boards and collects the digitized data for storage in non-volatile flash memory. Two lithium-polymer batteries provide the energy necessary for the proper operation of the entire on-board system. The following figure shows the final instrumented model and the main electronic sub-parts.
After the firing and the recovery of the probe, the data recorded during the flight is downloaded via a USB link by the associated management software whose following figure shows a preview.

3.2 Bore powder gun

Models are launched from a classical 91 mm smooth bore gun, length 2.73 m, at atmospheric conditions over a flight distance of 23 meters. In order to hold the sub-caliber model in the gun barrel, special sabots were designed. After exiting the gun muzzle, sabots petals separate from the models after a distance about 16 meters. Then, the model is considered to be in free-flight.
The radar Doppler, placed just before the PSP set-up, measured a speed between 238 m.s^{-1} and 254 m.s^{-1} according to the different tests.

Fig. 7. ISL Powder gun DEFA 90L30

4 Method for free flight measurements

4.1 Set-up

The method consists of taking simultaneously the reference image and the measurement image according to the intensity PSP method.

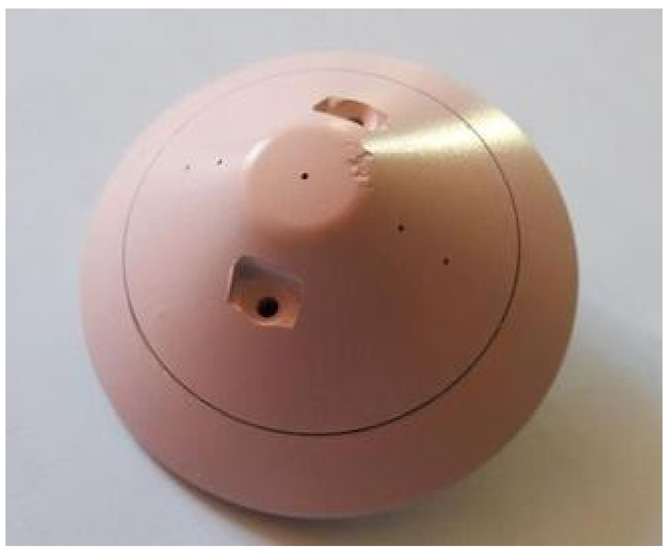


Fig. 8. Model with PSP

For this, we used a dichroic filter positioned at 45° to separate the luminescence signal. Under 495 nm, the signal passed through the filter for the reference image (reflection 98 %). Between 550 nm and 725 nm, the signal is reflected by the filter for the measurement image (transmission 90 %).

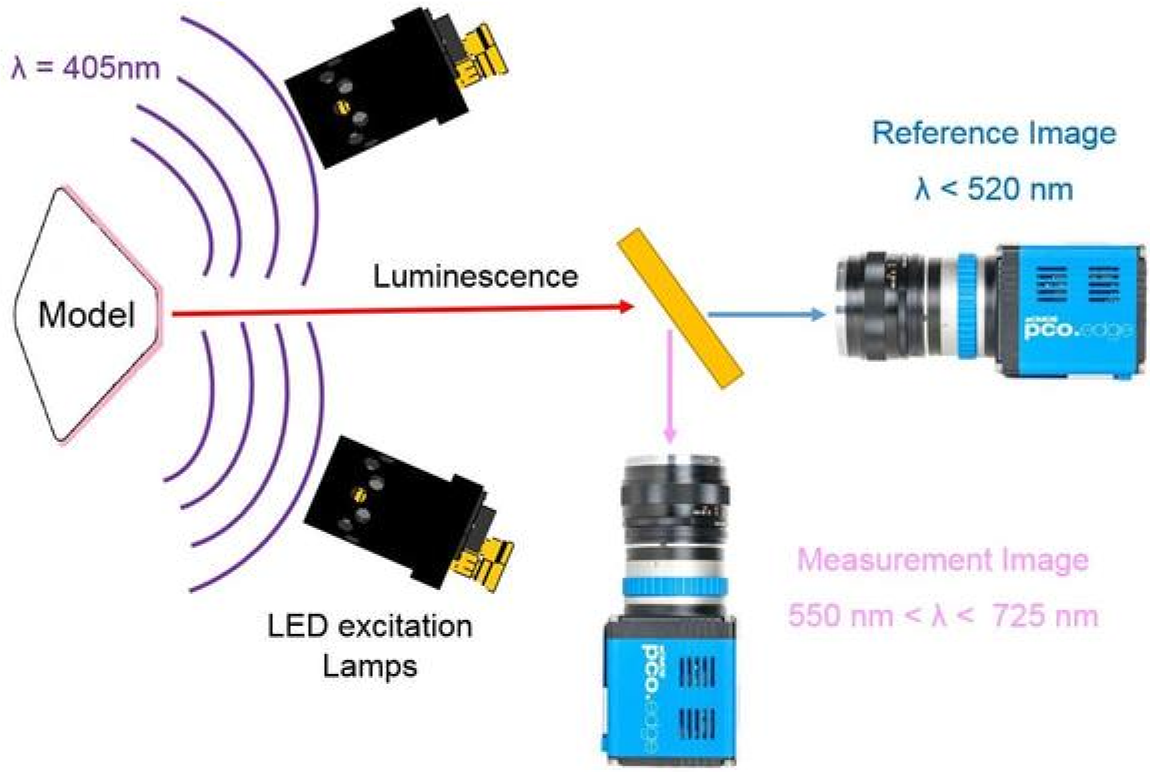


Fig. 9. PSP Free-Flight Principle

Luminescence images are recorded by CMOS high speed camera SA-X from Photron. The camera frame-rate is 50'000 images per second with a time expose of 17.20 µs. This generates a blur of few pixels which are treated with the post-processing tools. Each high-speed camera is equipped by Carl Zeiss lens Otus 55mm f/1.4 to obtain the best quality possible.

Fig. 10. High-speed camera SA-X

Fig. 11. Carl Zeiss Lens OTUS 55 mm

The difficulty is the large difference between the intensity for the reference at 400 nm and the intensity for the measurement at 650 nm. Indeed, there is a factor of 40 between the two. The reference image has a very low signal intensity at this wavelength.

4.2 Calibration

A calibration system has been developed to characterize the luminescence levels according to our own flow conditions. Notably, we have to determine the influence of the dichroic filter to separate the reference signal from the measurement signal, and validate the good linearity.

Fig. 12. PSP calibration system

The figure 13 shows the division between the image at 4 mbars and the image at 1 bar. The variation is about 2 %, due to some reflections inside the test chamber.

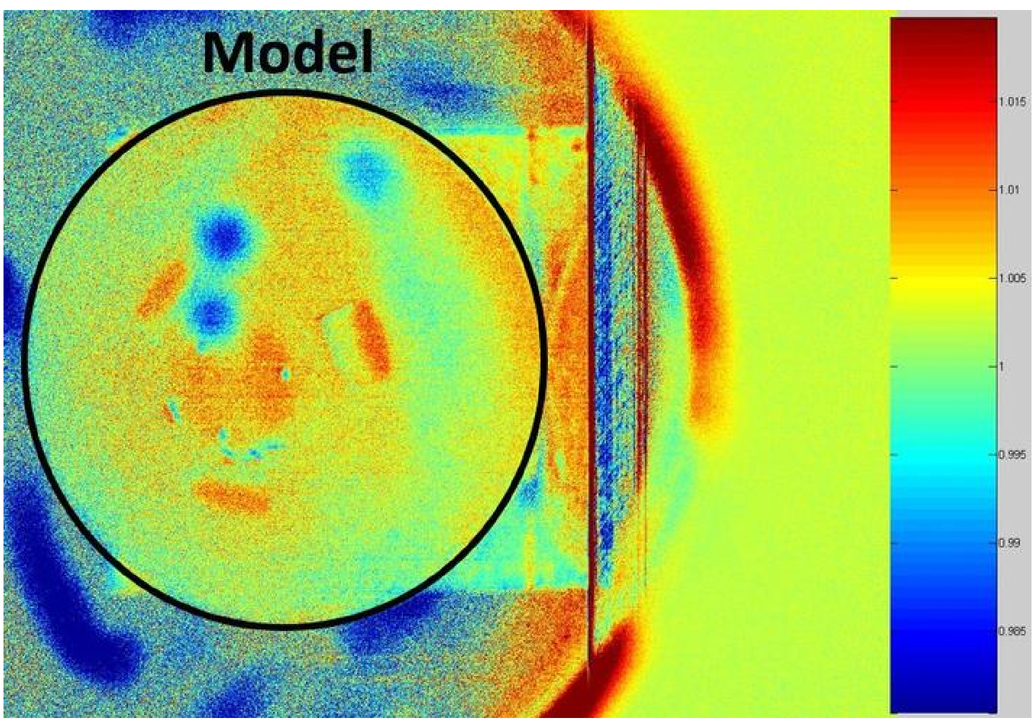


Fig. 13. Reference image independent of the pressure

As the reference and the measurement images are recording at the same time, the calibration must be done for each measurement with the same setting camera and lens (focal, aperture), and because the paint deposit is not always the same (with also the photo-degradation of the paint with the time, about 1% per hour).

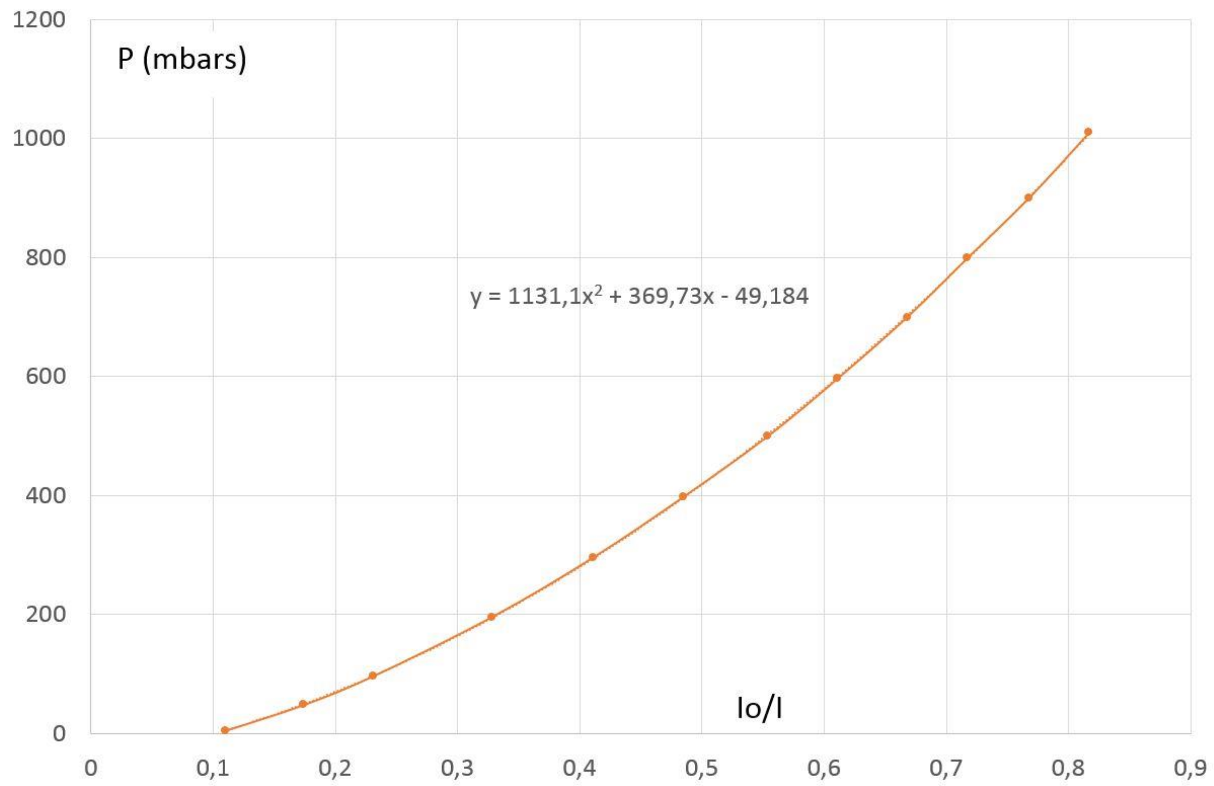


Fig. 14. PSP calibration example

The calibration also includes the influence of the excitation intensity, and the angle of observation between lamp, camera and model.

5 PSP measurements

5.1 Experimental set-up

The set-up is composed of two SA-X cameras, one for the reference image and the second for the measurement image, separated by a dichroic filter. The illumination is provided by two water cooled LED lamps. An optical barrier ensures the triggering of the recording. The distance model filter is 60 cm. The model come to the right with an angle of 30° compared to the axis set-up.

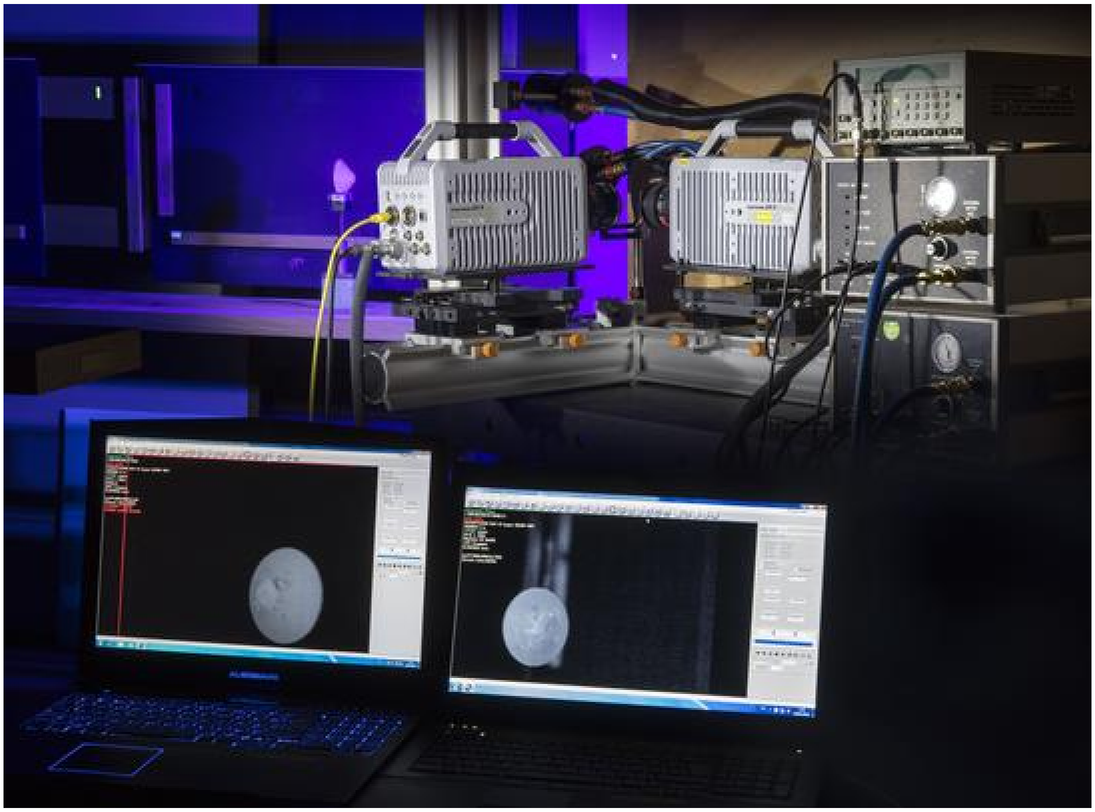


Fig. 15. Experimental PSP set-up

5.2 Post-processing

A complete PSP processing software has been developed under Matlab environment at ISL and includes all necessary steps to extract pressure information: calibration of the paint, spatial positioning of projectile and cameras, exact image readjustment, generation of the mesh model for the 3D projection of the results on the projectile, post-processing to extract the results [3].

5.2.1 Deblurring of the images

Since the PSP images are taken during the model motion, the individual illumination time may not be too large. It is kept low in order to avoid blurring due to the motion undergone by the model during the illumination time. It has been set at 1/58117s. However, the velocity of the model is so that blurring is not completely suppressed. In order to have a longer exposure time, it has been decided to add the series of images. But before performing this operation, two steps are required: deblurring of individual images and image registration.

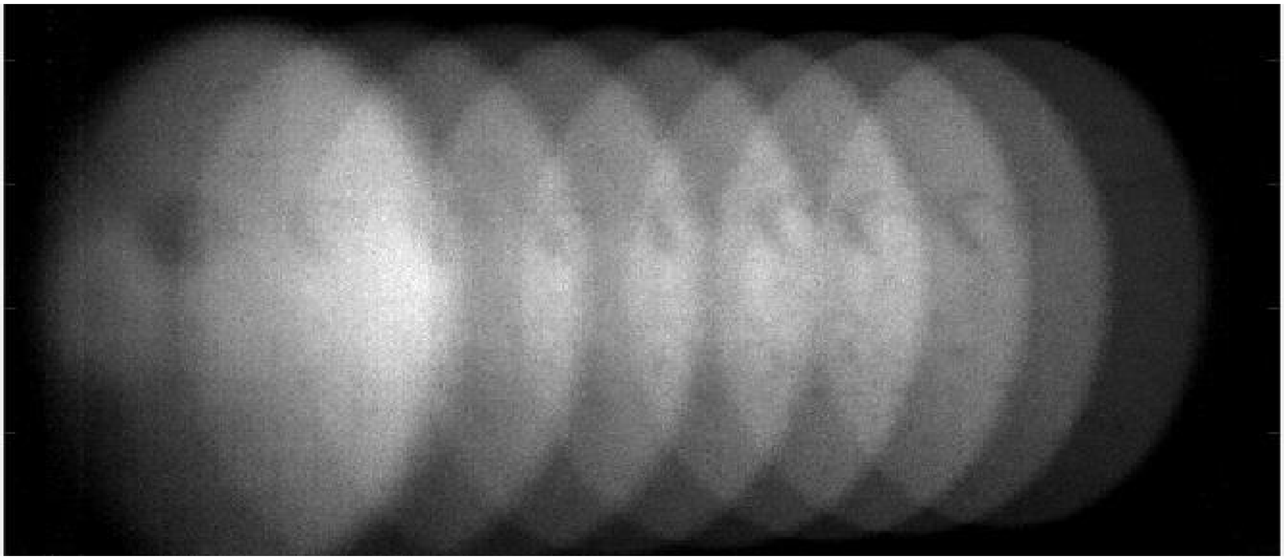


Fig. 26. Series of image represented on the same picture: model motion

5.2.2 Image deblurring

Image deblurring is performed thanks to a Matlab code based on the hypothesis that the blurring is uniform and due to the model motion. The kernel of the blurring filter is based on the calculation of the motion in pixels between two successive images. The inverse filtering is hence performed to recover the original image. Although this operation increases the level of details, it also increases the random noise on the individual images.

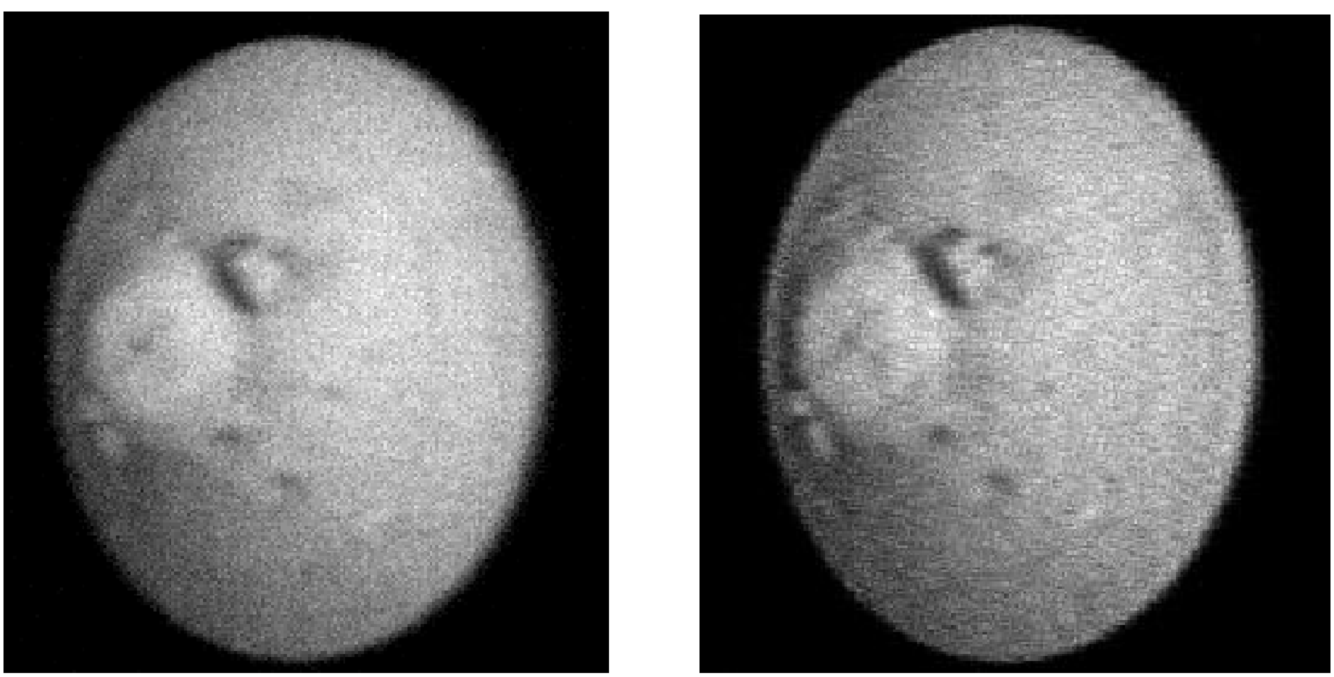


Fig. 17. Example of an individual image (left) and its deblurred image (right)

5.2.3 Image registration

Due to the fact that the model moves in front of the camera, adding the individually deblurred images may not lead to useful results. Image registration is used to enable the superimposition of the individually deblurred images.

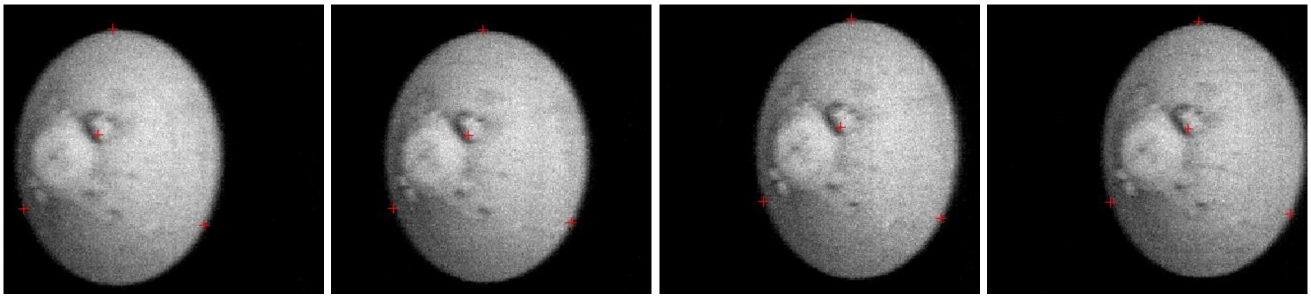


Fig. 18. Control points in image 1, 5, 9 and 12

A combination of a translation, a rotation and a scaling is assumed. A Matlab code has been developed in view to characterize the image transformation between two images. Four control points are used and determined for each image using a local correlation with the first image of the series. Based on the coordinates of the control points, the inverse image transformation is performed and the addition can be operated, as shown in the next figure.

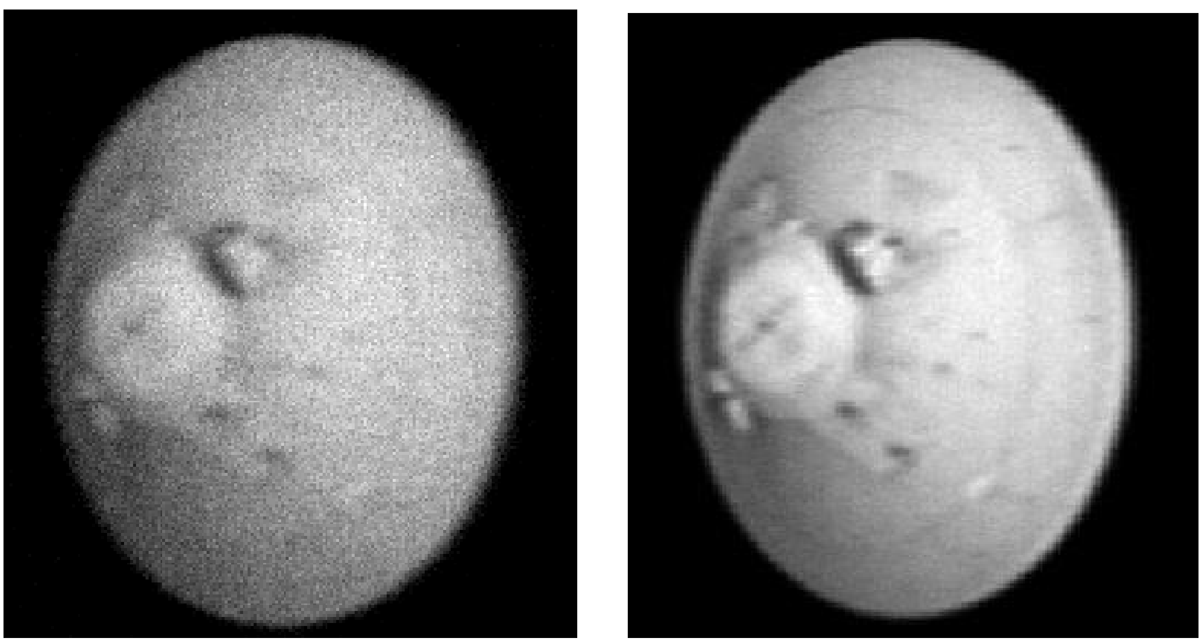
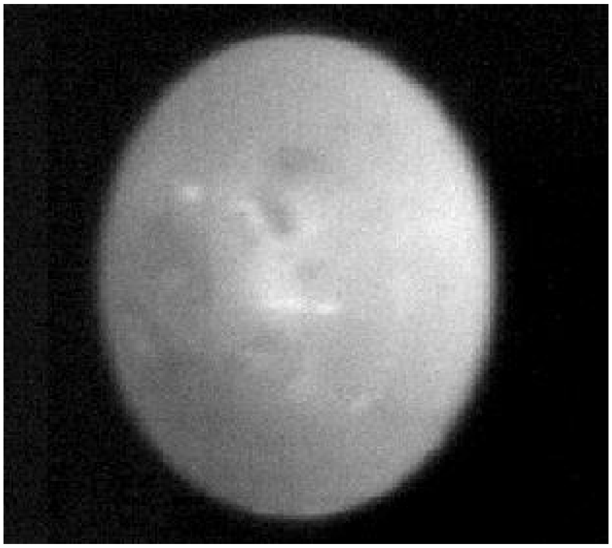


Fig. 19. Example of an individual image (left) and deblurred image (right) for the reflection image



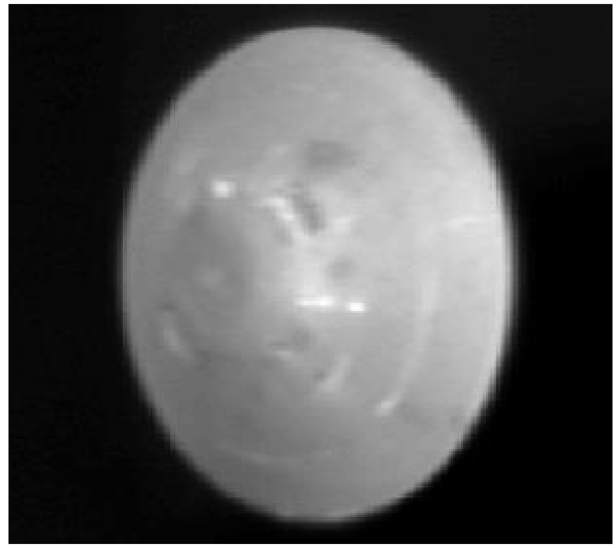


Fig. 20. Example of an individual image (left) and deblurred image (right) for the transmission image

5.3 Results

After the post-processing, we are able to align the reference image and the measurement image with translation, rotation and scaling process. Thus, we divided pixel to pixel the two images according to intensity method with the Stern-Volmer equation (1). With the calibration curve, we obtain the global pressure distribution.

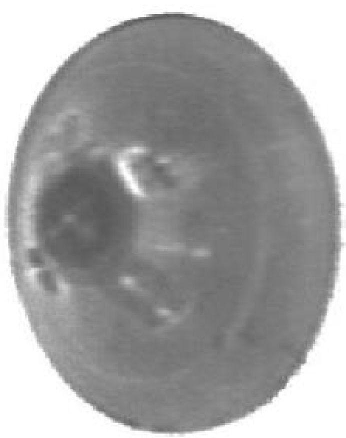


Fig. 21. PSP result after images division

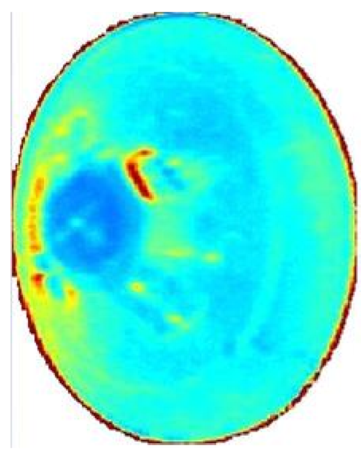


Fig. 22. PSP result

The distribution is relatively uniform, except at the center. This can be interpreted as a deterioration of the paint during the gun shoot by the support of the pusher plate.
However, due to the destruction of the model after the shoot, for this case, we are not able to calibrate the paint and convert the PSP division into qualitative pressure distribution.

5.4 Comparisons

5.4.1 CFD

Numerical Reynolds-averaged Navier-Stokes (RANS) simulations of the base pressure field are conducted using Fluent 15.0 ANSYS solver code with the kω-SST (shear-stress transport) turbulence model. Structured meshes containing of 1.5 million elements are generated with GridPro.

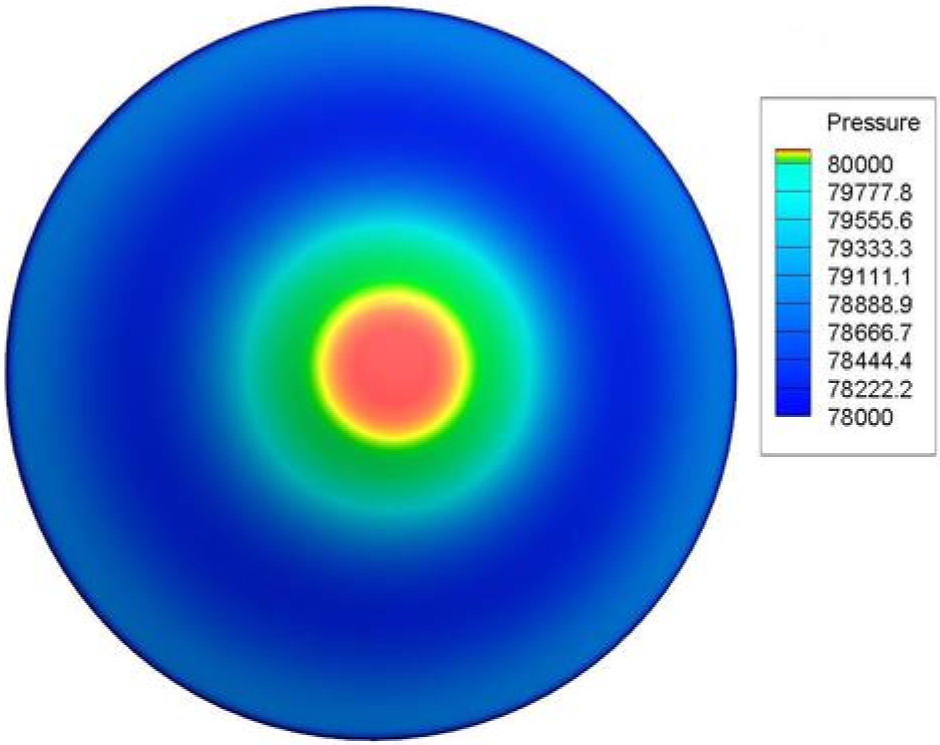


Fig. 23. Base pressure results from computation

Figure 23 shows the pressure distribution on the base of the model. The slight overpressure at the center of the model results from the RANS method and the non-resolved vortex structures in the base flow region typical for this simulation method. The global pressure is relatively uniform for a value of 800 mbars.

5.4.2 Pressure transducers

After the shoot, the distribution of the pressure on the model is relatively unsteady with am amplitude about 200 mbars. After 70 ms (17 meters), the pressure stabilizes around 850 mbars.

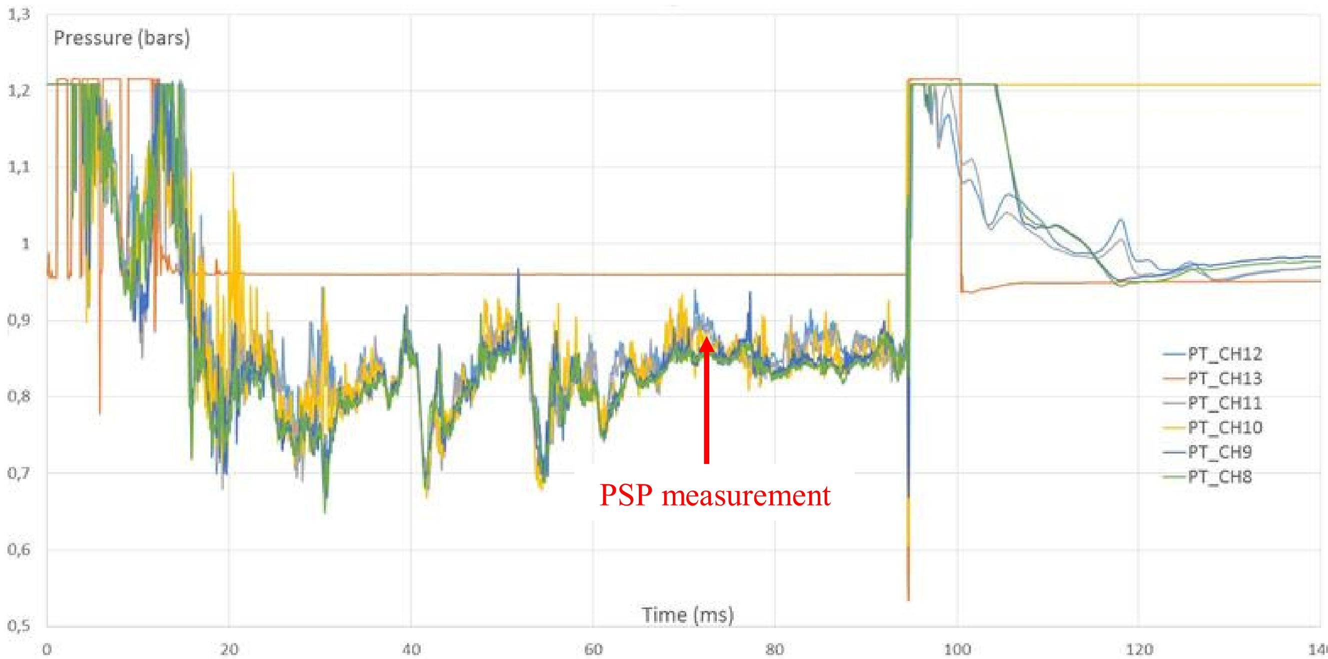


Fig. 24. Pressure transducers results

6 Conclusion

This article presents the development and the method to use PSP for free-flight tests. The principle of using a dichroic filter to record at the same time the reference image and the measurement image, is validated. For this, it is absolutely necessary to perform a calibration for each experimentation with the exactly the same set-up: camera, lens, filter and paint.

The post-processing to deblurring images allows to improve the quality of the images, and the signal to noise ratio. However, the PSP result accuracy can be improve. Especially, increasing the low level signal of the reference image. The next step is to use the news generation camera SA-Z, a custom dichroic filter to increase the luminescence of the paint, in order to obtain a better signal and accuracy.

References

[1] Engler R.H, The 8th International Symposium on Fluid Control, *PSP and TSP for different Wind Tunnel and Flow Facilities*, Measurement and Visualization, 2005.

[2] Liu T, Sullivan J.P, *Pressure and Temperature Sensitive Paints*, Springer, USA, 2005.

[3] Gauthier T, Martinez B, ISFVL13 – 13th International Symposium on Flow Visualization, *Multi-camera PSP Force Measurements at Supersonic Speed*, Nice, France, 2008.

[4] Albisser M, Dobre S, Berner C, AIAA Atmospheric Flight Mechanics. *Comparison of free flight base pressure measurements with CFD predictions*, Grapevine/TX, US, 2017

[5] Dobre S, Albisser M, Berner C, Saada F, Martinez B, Gnemmi P, 68th Aeroballistic Range Association Meeting. *Analysis of base pressure measurements in free flight*, Monterey/CA, US, 2017.