Optical Correction of Distortions created by Curved Window for L2F or LDA, 2D or 3D Anemometer Measurements in Turbomachine

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I. Intoduction

The transonic compressor has evolved into low aspect ratio, highly loaded configurations. Therefore, detailed and reliable experimental data are needed to map complex 3D flows within stationary and rotating blade rows. Laser anemometry is an ideal technique for such experimental investigations: Two Focus technique (L2F) since it has a high spatial selectivity, which makes it possible to measure velocities very close to surfaces, and Doppler technique (LDA) for accessing to the Reynolds stress values. Thick flat glass windows (named shroud windows), that typically provide optical access to the flow field, generate a mismatch between the window surface and the true shroud contour, which can induce large aerodynamic perturbations, essentially in transonic or supersonic fields [1]. In order to avoid this effect, curved windows can be used but the curvature leads to optical distortions of the laser beams passing through them.

In the case of L2F-2D anemometry, focusing two light cones creates the two spots of the probe volume [2]. Crossing the curved window, the spots are both enlarged and distorted, that leads to a decrease in the spatial resolution, to an increase in the mean and fluctuating values uncertainties and to a loss in the light intensity scattered by the particles passing through the measurement volume. These distortions, which increase with the immersion of the probe volume, hinder the creation of acceptably focused spots in the measurement volume and could even prevent the acquisition of no dataat all. Thus, an original optical assembly was proposed by Ottavy et al. [3], which consists in inserting a simple and inexpensive corrective window between the frontal lens of the anemometer and the shroud window. To determine the geometric characteristics and the position of this corrective window, a simplified analytical method was first developed, and then a more sophisticated numerical method was elaborated. We briefly recall the main points of this study here.

In the case of L2F-3D anemometry, an adaptation of the present method is needed. Recall that the L2F-3D anemometer is composed of two L2F-2D devices, which are symmetrically located on both sides of its axis, and that the procedure consists in acquitting data at different angular positions of the anemometer [4]. The angles between the laser beams axes and the normal to the window are changing during the rotating movement. Thus, the optimisation of the corrective system is a priori more difficult because it is subordinate to the anemometer angular position. Furthermore, it is desirable that the geometric characteristics of the measurement volume remains unchanged whatever the angular position is.

In the case of LDA anemometry, the problem is rather different. The measurement volume, for each component of the velocity vector, is obtained by crossing only two thin beams. Several authors [5] have shown that, even if, in most cases, these distortions do not hinder acceptable measurements, they lead to an increase in uncertainties in the measurement, with nevertheless more serious implication to a correct evaluation of the RMS values. This is caused both by deformation of the measurement volume and by changes in the measurement location. The necessary conditions for creating each fringe volume is that the two corresponding laser beams effectively intersect themselves and, if possible, in their focalisation zones. It is the reason why, using the numerical method previously developed to optimise the corrective system, a new procedure has been adapted for that specific purpose.

II. Problem analysis and remedies

The measurement volume of laser anemometers is composed of focusing laser beams whatever the system is (L2F or LDA, 2D or 3D). Firstly, to analyse the problem, let us consider only one laser beam.

Assuming this laser beam can be approximated by a light cone, light rays inside this cone travel different paths from the front lens to the focus point. Consequently, the incidence angle of each ray on a curved window inserted between the lens and the focus point, will vary. Those differences of incidence values increase with the beam radius and the radius of curvature of the curved window. Each beam is then deflected differently through the window, whence a shift a and distortion of the focusing zone.

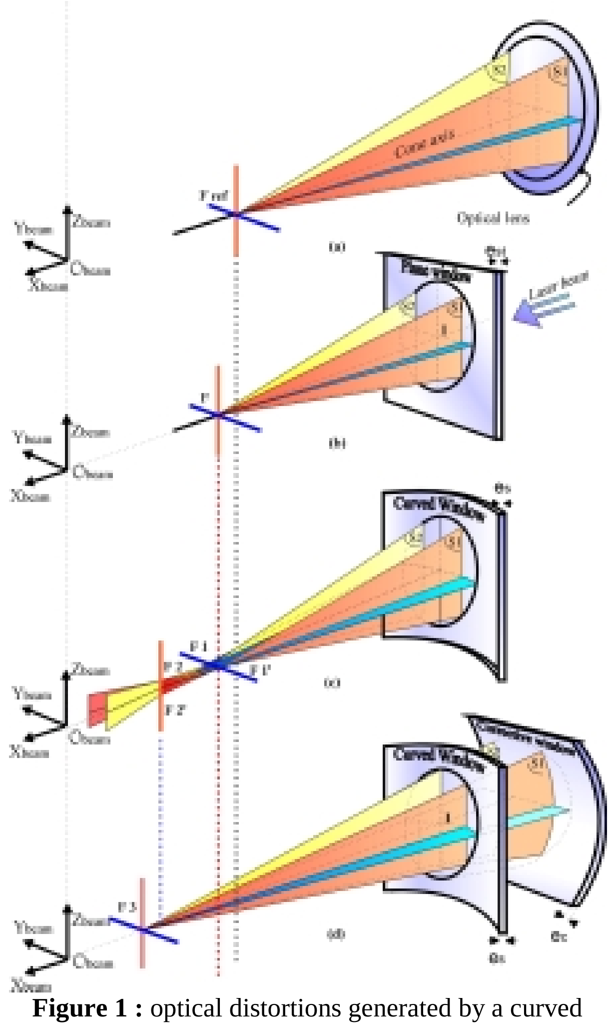


Figure 1 : optical distortions generated by a curved window

In order to explain those phenomena, let us consider two sets of light planes within the laser beam (Figure 1 (a)). The first one is composed of the "vertical" type surfaces (i.e. normal to the (X_{beam},Y_{beam}) plane), like S1 and S2, and the second one of the "horizontal" type surfaces (normal to the latter). The intersection of those vertical planes is the thick vertical line, and that of the horizontal planes is the thick horizontal line. Each of those is centred about F_{ref}, which is the top of the incident cone issued from the front lens of the optical system. In Figure 1 (b), a plane window is placed, orthogonal to the axis of the light cone, in between the focal point and the lens. Since the angle of the light cone is small (typically <5°), the focal point can still be assumed to be a point, although its location is changed.

Let us replace the plane window by a curved window of identical thickness with a radius of curvature R_s, and an axis parallel to (O_{beam}, Z_{beam}), as shown in Figure 1 (c). The horizontal planes remain unchanged by the glass: they intersect as in (b) at point F. On the contrary, the vertical planes S1 and S2 are deflected due to the glass curvature and intersect downstream from point F. The resulting effect is the appearance of two zones where light is concentrated: [F_1,F1'] at the intersection of the horizontal planes, [F_2,F2'] for the vertical ones.

We now proceed to explain Figure 2 the shifting of zone [F_2,F2'] with respect to [F_1,F1'], by considering the special case of turbomachinery, in which curved shroud window is present. In that case, the measurement volume immersion value is necessary less than the radius R_s of the shroud (case of laser beam *a* only). Therefore, the light rays impacts upon the window from above. In this configuration, the focal point F_a' is located beyond the focal point without window. This explains why vertical planes cross downstream from point F (zone [F_2,F_2']).

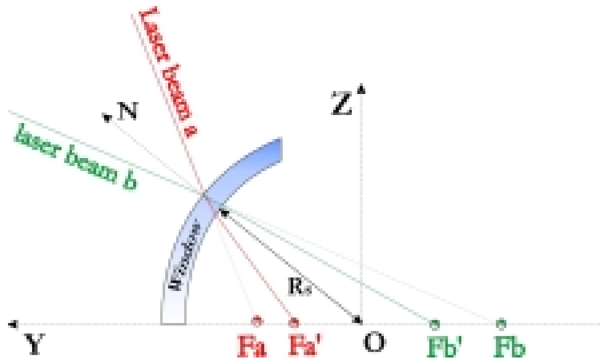


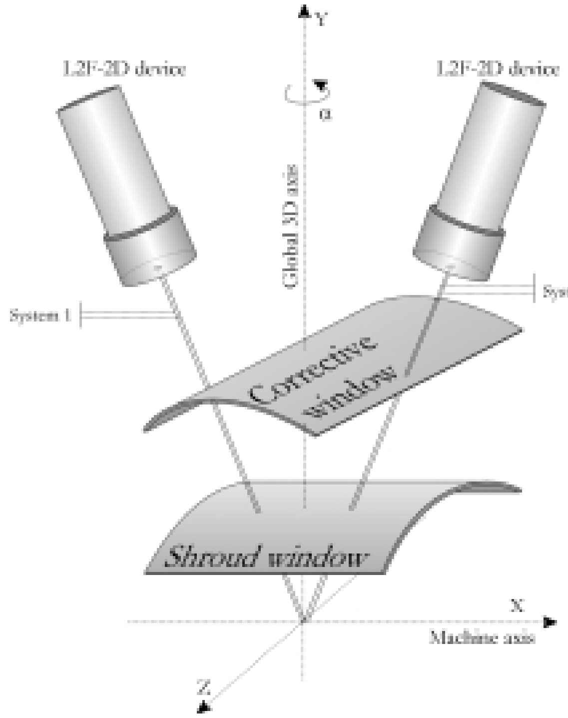
Figure 2 : Effect of curvature on beam path

The two areas [F_2,F2'] and [F_1,F1'] move away from one another when the thickness e_s of shroud window increases, and the radius of curvature R_s decreases. For characteristic scales in turbomachinery domain, such a displacement can amount to 0.5 mm.

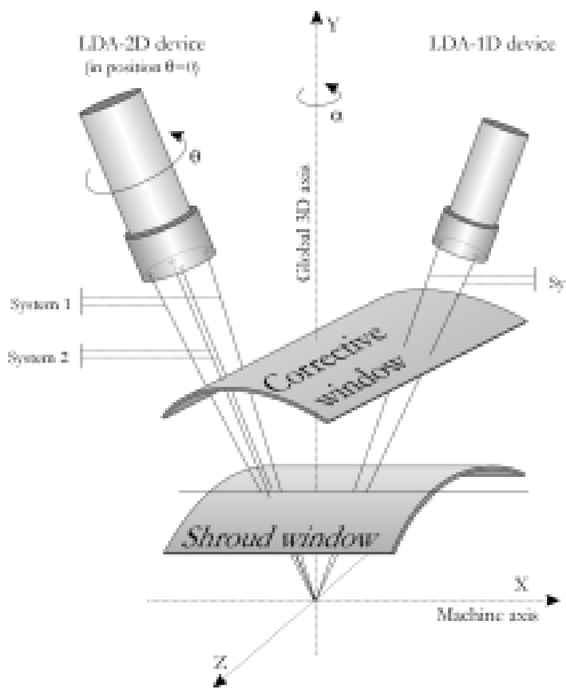
In order to compensate the optical deviations induced by the shroud window, a second cylindrical window (so called "corrective window") of axis parallel to (O_{beam}, Y_{beam}), is introduced (Figure 1 (d)). The purpose is to create optical distortions for the horizontal light planes similar to those for the vertical ones. A judicious choice of the thickness e_c and radius R_c of the corrective window, as well as of the distance L_v between the two windows, allows us to bring the intersection of horizontal planes [F_1,F_1'] to the same location as that of vertical planes [F_2,F_2'].

III. Application to L2F and LDA devices

A numerical simulation has been previously developed [3] for L2F-2D anemometers. This tool permits an accurate knowledge of distortions and displacements of laser beams induced by shroud windows and then to optimise the corrective device. This corrective system has been successfully used to perform L2F-2D measurements in an axial transonic compressor [6]. The purpose of this paper is to present the extension of this correction method for the use of L2F-3D and LDA devices.



(a) : L2F-3D Device



(b) : LDA-3D Device

Figure 3 : Schematic view of L2F-3D and LDA-3D experimental set-up

III.1. Specific problem for L2F-3D system

In 2D configurations, the L2F device turns round its optical axis during the angle-scanning procedure. Both beams of this system being very close one from each other, the global geometrical configuration doesn't really vary during the procedure. In the three-dimensional case, the problem is more complex because both 2D devices constituting the 3D-system turn round the global 3D axis (and not round their own optical axes), which could induce a different geometrical configuration for each angular position (Figure 3 (a)). So, a new question is appearing, on the possibility to optimise an L2F-3D device with a unique corrective window overall the angle scanning range, and on the necessity to readjust its position during the rotation.

Remember that presence of curved windows induces both distortion and displacement of the focusing volumes. The relative displacement of those volumes can induce uncertainties on the 2D components of the estimated velocity. Furthermore, the third component of the velocity vector being directly linked to the angle γ between both systems, it is also very desirable that this angle remains constant, or at least known, after windows crossing.

This study points out that it is possible to obtain a satisfying correction, for the whole-explored angular band, with a single window at a fixed position. The reliability of this corrective procedure is highlighted after, by comparative measurements in a test case.

III.2. Beams coincidence for LDA device

For a LDA anemometer, it is the quality of the interference fringes, created by the crossing of two thin laser beams, which conditions those of the measurement. A displacement of the focusing points affects, or can prevent beams intersections.

Remember that an LDA-3D system is composed of three LDA-1D systems (included in two 1D and 2D devices: Figure 3 (b)). Each measurement volume of those three devices is generated by the intersection of the two beams constituting the device (we will speak of "intra-system" coincidence). Any displacement of the multiple focusing volumes induced by windows, may lead to a total disappearance of intersections, then of the measurement volumes. The objective of this study is to adapt the correction principle, presented above, for such LDA devices, by controlling these displacements in order to maintain "intra-system" coincidences.

IV. Numerical results

The numerical simulation has been extended in this study for L2D-3D and LDA systems. This tool permits an accurate knowledge of the laser beams distortions induced by windows, and then to optimise L2F or LDA corrections considering the most important purpose for each of them: quality of focusing for L2F systems, and "intra-coincidence" for LDA systems.

The thickness e_s and curvature R_s of the shroud curved window used for calculations are respectively 3 mm and 256 mm. The immersion deepness is 50 mm.

IV.1. L2F-3D device

The geometrical characteristics of the corrective system are here obtained by a numerical optimisation leading to a minimal size of the measurement volume for the range $\alpha\in[0,90°]$ (Figure 3). The thickness e_c, curvature R_c and windows-spacing L_V obtained are respectively 1.9 mm, 472 mm and 149.3 mm.

Results are presented for an angle α=90°, representative of the most unfavourable case.

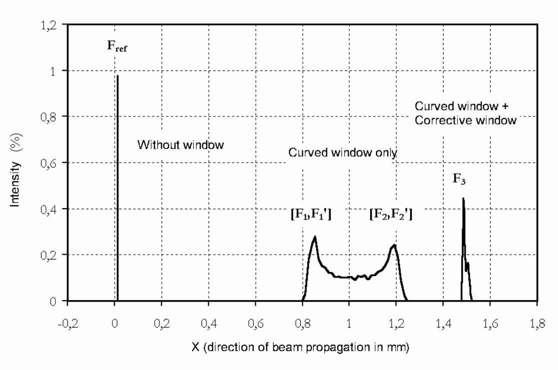


Figure 4 : Numerical repartition of intensity along the beam axis in the focusing volume

Let us present in Figure 4 the numerical repartition of intensity in the focusing volume along one beam axis (other beams results are not presented because very similar). Those results show exactly phenomena introduced in II. The presence of a corrective window restores a quality of focusing comparable to the case without window. The gain on longitudinal size and intensity is indisputable: size decreases from 400 µm without correction to 50 µm with corrective window. It looks possible to compute an optimal geometric configuration for the corrective window, permitting a high-quality focusing all over the range for angle α.

Furthermore, this simulation gives an estimation of the geometrical characteristics of L2F measurement volumes. Table 1 presents relative variations of the distance δ between the two focusing volumes forming the measurement volume and the values of the angle γ between the two L2F-2D systems of the L2F-3D device, after having crossed the shroud and corrective windows. We can observe that, for very unfavourable values of (φ,θ,α), the variation $\Delta\delta/\delta$ remains very low (less than 1.5% for a nominal value of 425 µm for δ). For the angle γ, we see that it suffers very few variations too (less than 0.05°).

φ	θ	α	$\Delta\delta/\delta$ device 1	$\Delta\delta/\delta$ device 2	γ
0 °	0 °	0 °	0.327 %	0.765 %	15.014 °
10 °	10 °	0 °	0.339 %	1.512 %	15.014 °
10 °	10 °	80 °	0.114 %	0.329 %	15.05 °
20 °	20 °	80 °	0.145 %	0.287 %	15.058 °

Table 1 Variation of relative inter-spot distance $\Delta\delta/\delta$ and of angle γ between both systems, for different geometrical configurations, with and without corrective window

IV.2. LDA-3D device

In this part, let us consider a geometrical configuration that is typical in turbomachinery applications: the global 3D axis is radial i.e. normal to the shroud window. Remember that θ does quantify the rotation of the 2D device round its own optical axis. It is rather preferable to work with θ=45°, position which reduces the necessary access through the window (in Figure 5: d_0>d_{45}), permitting deeper immersions.

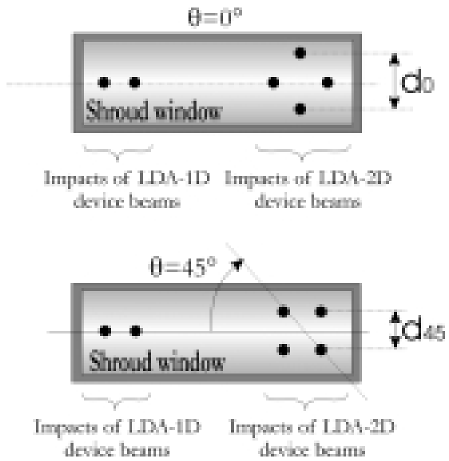


Figure 5 : Orientation of the 2D device for maximum flow immersion

Results presented in Figure 6 show the evolution with θ of the minimal distance δ_{min} between the two beams of each LDA-1D system of the LDA-2D device (systems 1 and 2, Figure 3), normalised by the beam waist ω_0. They are presented with shroud window, with and without corrective window. The corrective window location and characteristics have been computed for an optimal intra-coincidence of all three systems. Since the calculated window is geometrically very close from the one in L2F case (IV.1), we still consider the same geometrical dimensions. The windows-spacing L_V changed to 154.6 mm.

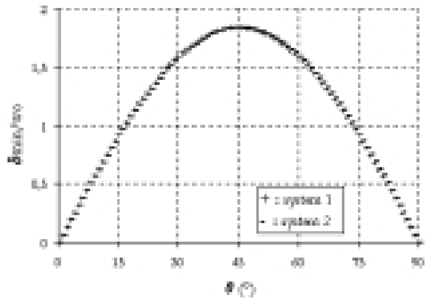
The 1D device (system 3) results are not presented because always disposed in a symetrical plane of both windows: the two beams of this system always intersect (they behave like the device 1 in position θ=0°).

If we look at the coincidence, with shroud window only, θ=45° is the worst configuration. Such an angular position makes the distance between both beams of systems 1 or 2 nearly reaching twice the beam waist radius ω_0: beams don't intersect, and the measurement volume can't be created. When the corrective window is added, this distance doesn't reach 0.007 ω_0 (Figure 6): such a coincidence can be considered as perfect.

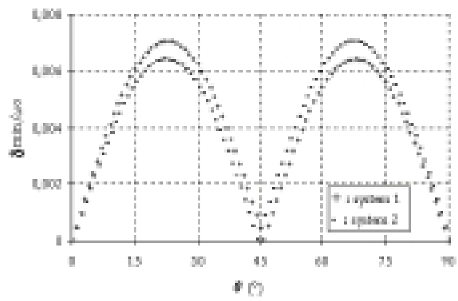
In addition, we note in Table 2 that the characteristic longitudinal sizes σ_L of focusing volumes of each beam are significantly reduced, thus revealing a focusing amelioration.

System		$\sigma_{L\ \text{without correction}}/\sigma_{L\ \text{with correction}}$
1	1rst beam	5.434
	2nd beam	3.393
2	1rst beam	3.393
	2nd beam	5.434
3	1rst beam	5.857
	2nd beam	3.082

Table 2 : Improvement of focusing quality for a LDA-3D device



(a) : Shroud window only



(b) : Shroud window with corrective window

Figure 6 : Evolution with θ of the distance between both beams of each LDA-1D system of the LDA-2D device

Previous results could let us think that for a position θ=0 or θ=90°, coincidence problems don't exist, and that the simplest solution would be to work with those configurations. Indeed, the two beams, whatever the device, would evolve in a symmetrical plane for windows then with plane propagation: they would ever intersect. The problem is however not so simple if we observe where do beams intersect. Following results are exposed for the system 1.

Let us construct a co-ordinate system based on one particular beam of this system 1, which centre is the focusing point, since the propagation axis is supported by X_{beam}. Y_{beam} is normal to X_{beam} in the plane of both beams. Figure 7 represents the relative location of the intersection with the second beam, for the positions θ=0° and 90° without correction, and for positions θ=0°, 45° and 90° with correction (the position θ=45° is not represented without correction, as we saw measurement volume doesn't exist). The Figure 8 represents the relative location of the focal point of the second beam. All values are normalised by the characteristic sizes of the focusing volume: the longitudinal length $2L_0$ along X_{beam}, and the radius at the focal point ω_0 in the (Y_{beam}, Z_{beam}) plane. The red ellipsoid (the thinnest one) represents a distance inferior to the half of the focusing volume size along the considered direction, i.e. an acceptable coincidence. The blue one represents a distance inferior to the focusing volume size along the considered direction: on the outside of such a limit, we can consider than measurements are quite impossible.

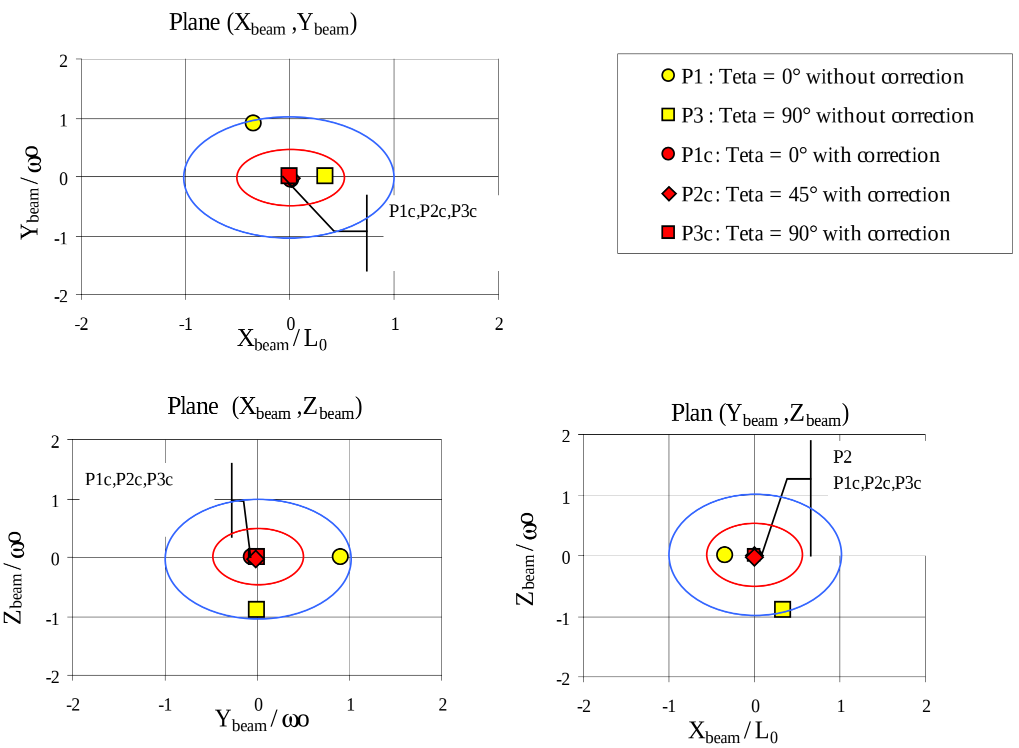


Figure 7 : distance between the intersection of the two beams of system 1 and the focusing point of one of those beams, for different values of θ.

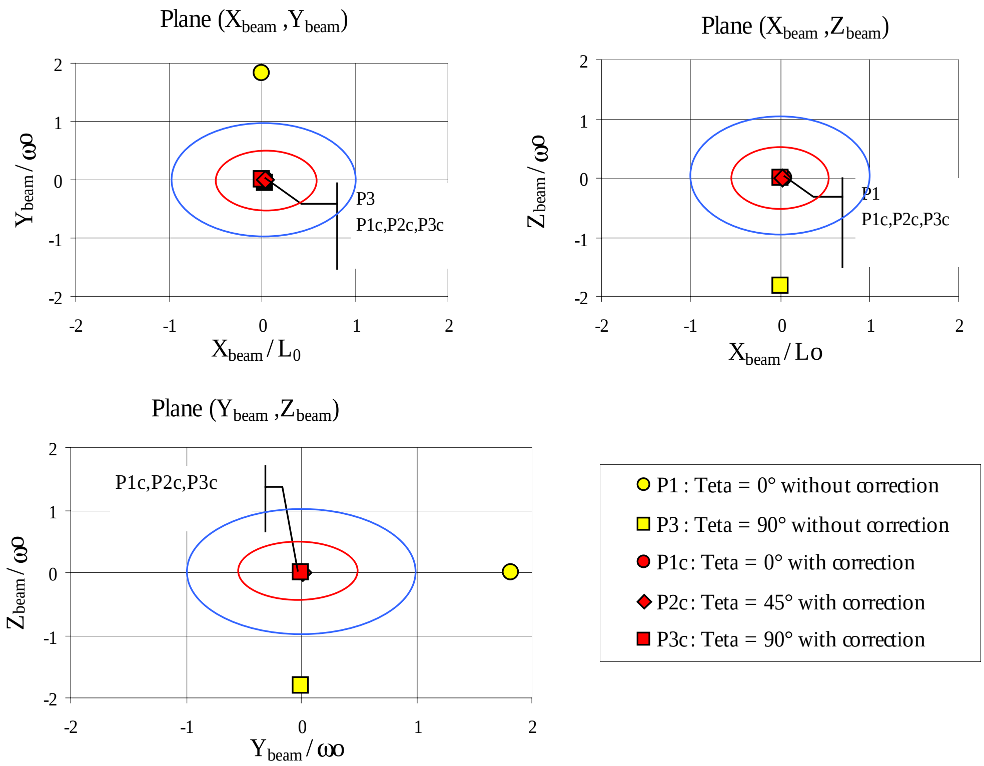


Figure 8: distance between the two focusing points of each beams composing the device 1, for different values of θ.

The configurations θ=0° and θ=90°, which ones were appearing as perfect without corrective window, prove here to be problematic. Figure 7 shows that, if influence of windows on the axial relative location (X_{beam}) of focusing volumes is not consequent, it is not the case for the tangential displacements (Y_{beam}, Z_{beam}). Both beams of the same device do not intersect themselves at their respective focusing volumes. This has a direct impact on the focusing volume quality, and on the fringes pattern and could conduct to very important uncertainties. With corrective window, the two beams intersect at their respective focusing volumes with a high accuracy, for each position of θ : coincidence can be considered as perfect.

In this geometrical configuration, it is possible to optimise the “intra-system” coincidences of the three systems that constitute the LDA-3D device with a sole corrective window. This optimisation leads to a spacing L_V of 89.7 mm between the two windows, and the calculated distance δ between the focusing volumes of each beam of each system is given in Table 3.

	System 1	System 2	System 3
δ / ω_0	0.106	0.106	0

Table 3 : Optimisation for “intra-system” coincidences of a LDA-3D device with an unique window

Correcting a 3D device with a unique window becomes more problematic when the global 3D axis is not normal to the shroud. It may be necessary to use two windows, one for each device.

We can conclude that, in the case of this study, a unique window allows at the same time to improve the quality of the measurement volume and to lead to a “intra-system” coincidence for each of the three systems constituting the LDA-3D anemometer.

V. Experimental validation

The efficiency has been tested on basic experiments, as well for L2F-3D than for LDA-3D devices.

V.1. L2F-3D device

As for the calculations performed in the numerical part, three cases have been tested: without any window, measurement through a shroud window normal to the global 3D axis of the used device, and measurement through a shroud and a corrective window (still normal to the 3D axis). The characteristics and locations of the shroud and corrective windows are the same than for the numerical study. For each case, the longitudinal size of the measurement volumes have been experimentally estimated, by measuring the luminous intensity reflected by a plate, located at different axial positions in the laser beam.

Let us present on Figure 9 the experimental repartition of intensity in the focusing volume of the beam, along its axis, for three angular positions of the anemometer: α=0° (both optical axes of both 2D-devices in the meridian plane of the shroud window), α=45°, and α=90°. We can observe that the double focusing analytically and numerically predicted is always present. The shroud window moves away the focal point from F_{ref} to [F_1,F_1’], of approximately 0.7 mm, and the curvature of the glass induces a longitudinal distortion of 0.5 mm (distance between zones [F_1,F_1'] and [F_2,F_2']). Those displacements and distortions can not be ignored.

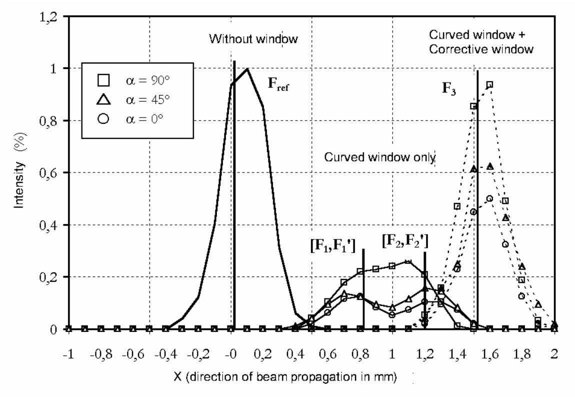


Figure 9 : Experimental repartition of intensity along the beam axis in the focusing volume, for 3 values of α

The corrective window sends away [F_1,F_1'] and [F_2,F_2'] focusing into F_3, and restores high quality focusing : the obtained signal looks gaussian, and the location of the measurement volume is invariable, for any angular position. We observe some differences in the signal magnitude, probably due to the fact that incidence angle increases when α decreases : the part of light reflected by windows (i.e. lost) is then more important. Let us remark the high concordance with numerical results: location and longitudinal size of the focusing volume are perfectly predicted by the numerical program (vertical lines). Those experimental results validate the developed numerical program ones.

Those results confirm that influence of rotation of the optical system is low, and that it is possible to find a unique correction that may be used at least for a large range of angular positions of the device, what is fundamental for the angle scanning procedure. This corrective assembly allows also measurements when the presence of noise addicted to the distortions due to the windows made them impossible.

V.2. LDA-3D device

An experimental assembly has been built in order to validate the corrective system for LDA-3D devices.

The geometrical configuration is the same than for the numerical simulation (θ=45°, same windows), except the immersion which has been chosen a little deeper in order to increase distortions, and then to visualise easily the phenomena. The optimal position of the corrective window is computed taking the coincidence criterion into account.

The LDA device focuses on a very short focal length lens, then permitting the optical projection on a screen of planes normal to the global 3D axis (magnification of about 900). It makes possible to estimate the distance between beams in such planes. Replacing the lens by a plate, we also measure the intensity along the axis, as well as for the L2F-3D case, acceding to the locations of each focusing volume.

For this test case, we have determined with and without corrective window:

- The coincidence, i.e. the minimum distance δ_{min} between both beams of a same system, measured in a plane normal to the 3D axis.
- The longitudinal displacement ΔX of the focusing volumes along the 3D axis, when adding shroud and corrective windows.
- The longitudinal distortion of the focusing volumes.

a. Coincidence

While beams of the 1D device (system 3) can be placed symmetrically to system 1 or 2 (with a same angle of 45°), it will benefit from the correction of the 2D device (since global axis is normal to the window) ; otherway, it is possible to correct this system with a second corrective window. Then, we just consider the systems 1 and 2 (2D device). Furthermore, the symmetry associated with the position θ=45° leads to the same results for each of both systems of the 2D device.

The measurements of the diameter of projected volumes on the screen are obtained with an uncertainty of 3 mm, what represents about 6% of the beam waist.

Figure 10 shows the view of the projected volumes on the screen, in the right proportions, and Table 4 presents experimental and numerical values of δ_{min} with and without corrective window.

While beams from systems 1 and 2 didn't intersect, the presence of the corrective window restores an accurate measurement volume. Furthermore, we observe a very good agreement between the measured values and the numerical predictions.

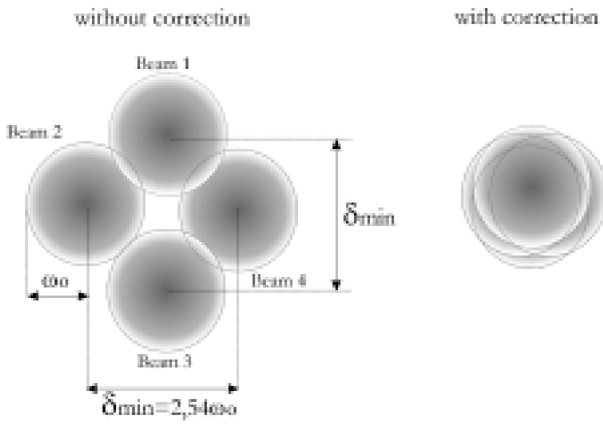


Figure 10 : view of the projected volumes on a plane normal to the 3D axis

		$\delta_{min}/\ \omega_0$
Experimental	Shroud window only	2.54
	Shroud window + corrective window	<6% (accuracy)
Numerical	Shroud window only	2.4
	Shroud window + corrective window	1.6 E-7

Table 4 : Experimental and numerical values of beams spacing δ_{min}

b. Location and distortion of focusing volumes

Figure 11 presents the repartition of intensity, along the global 3D axis, of one of the laser beams from the system

1 (other systems lead to similar results). If we define the length of the measurement volume $2L_0$ at a height of 10% from the maximum intensity level, Figure 11 leads, with ω_0=30µ, to the following values:

$L_0 = 25\omega_0$ for the case without any window.

$L_0 = 30\omega_0$ for the case with shroud window only.

$L_0 = 25\omega_0$ for the case with shroud and corrective windows

The shroud window distorts and lengthens the measuring volume. The double focusing is less important than for the L2F case where focusing is stronger, but appears anyway. Even with an optimisation based on the coincidence and not on the quality of focusing, the corrective window restores on the one hand the length of measuring volume and on the other hand a repartition of intensity comparable to the case without window. The intensity level is nevertheless lower with both windows, because the reception lens of the LDA-3D device is not on the emission path: reflections are more important and affect the signal quality.

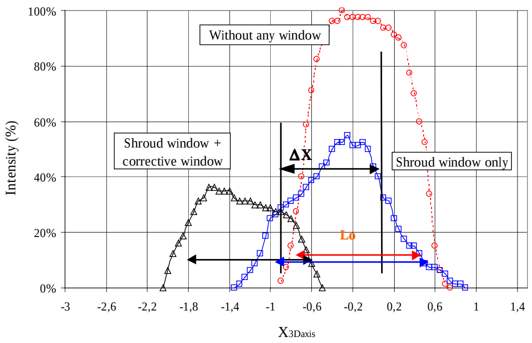


Figure 11 : repartition of intensity, along the global 3D axis, of one of the laser beams from the system 1

Table 5 gives the comparison between the measured displacement ΔX on the global 3D axis and the results given by a numerical calculation. But, as numerical results represent the displacement along the laser beam propagation direction, we have to consider a factor cos(20) (20° being the angle between the direction of the considered beam and the global 3D axis).

$\Delta X_{num}.\cos(20)$	ΔX_{exp}
1.108 mm	≈ 1.2 mm

Table 5 :Measured and computed displacements ΔX on the global 3D axis

Those results confirm once more the high coherence between numerical and experimental results.

VI. CONCLUSION

A numerical simulation has been developed to define the geometrical characteristics of a corrective lens and to predict displacements and distortions of the measurement volume. It has been successfully applied as well for L2F as for LDA anemometers. Numerical results have been validated by experiments on test cases.

This simple corrective system proves to be efficient: it restores a high quality of focusing in L2F technique and a perfect coincidence of laser beams in LDA technique. For basic geometrical configurations, a unique corrective window leads to an efficient correction for the global 3D system.

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