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THREE DIMENSIONAL LASER TWO FOCUS ANEMOMETRY FOR TURBOMACHINERY APPLICATIONS

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This study focuses on the statistical aspects of the three-dimensional L2F measurement method. Because the various quantities are not measured simultaneously, the calculation of the first and the second order momenta is not available without an non-correlated-variable-hypothesis. A critical test has been carried out in an axisymmetrical free jet operating in a way where 3D flow could be measured. Moreover, the turbulence intensity in this flow field could vary from 2% in the potential core to 50% in the developed flow area. Consequently, an analysis of the measurement method limitations and efficiency could be developed.

1. Introduction

Due to the increasing demand for improved performances and efficiency of the rotating machines, there is a growing need for methods to study and analyse the detailed flow behaviour. In this context, experimental systems allowing accurate measurement of the three-dimensional flow field in the rotating environment are needed.

The 2D-L2F technique, developed for fifteen years at the L.M.F.A., was extended by Schodl [1] for three-dimensional measurements in turbomachinery. Schodl along with his co-authors are the only ones, at the present, time to have carried out measurements with the 3D-L2F device. First of all, they have made a critical test around a sphere located in the potential core of an axisymmetrical jet to check the system performances [2], and they have presented some results at the exit of a propfan test rig [3]. In all these works, three components of the mean velocity vector and only two standard deviations have been presented but the way they were calculated has not been described.

In this paper, a statistical calculation method for one and second order momenta and the results of a critical test carried out in an axisymmetrical free jet are presented. The 3D-L2F is described first and followed by the statistical analysis, the measurements results and a conclusion dealing with the method limitations and efficiency.

2. Three-dimensional laser two focus system

2. 1. Measurement principle

The 3D-system consists basically in two 2D-L2F devices which are symmetrically located on both sides of its rotation axis with a slant γ of 7.5 degrees with regard to the symmetry plane. The two 2D-L2F systems measure the velocity vector projections in their respective focal planes (modulus u_i and direction α_i) from which the three spherical components of the total velocity can be calculated. In fact, for a single 2D device, the measurement is only possible if the velocity vector lies within the plane of the beams. In figure 1, one could see that the velocity vector which is in the symmetry plane is neither in the first nor in the second beams plane. Therefore, the velocity vector cannot be measured with any devices at that orientation. A small turning of ϕ_1 will bring the velocity vector in the beam plane of the first system and a counter rotation of $\phi_2= -\phi_1$ will bring the flow vector into the beam plane of the second one. If we call α the angle between the symmetry plane and an angular reference, two different angles $\alpha_1 =\alpha+\phi_1$ and $\alpha_2=\alpha+\phi_2$ could be measured. Nevertheless, because of the 3D-system symmetry, we get the same modulus u with the two 2D-devices.

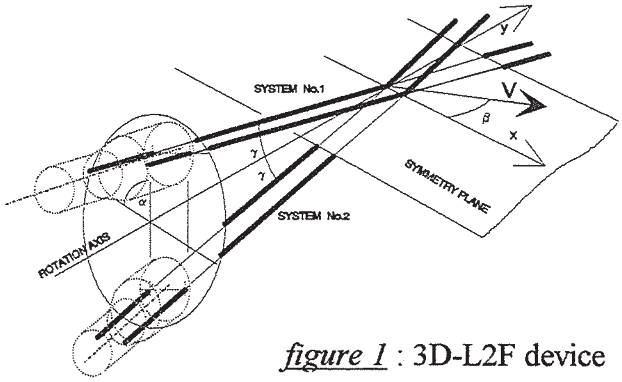


figure 1 : 3D-L2F device

The following relations between (V, α, β) and (u, α_1, α_2) can be derived from the geometrical situation (if we note $\delta=(\alpha_1-\alpha_2)/2$) :

$$\alpha = \frac{\alpha_1+\alpha_2}{2} \tag{1}$$

$$\beta = \arctan\left(\frac{\sin\delta}{\tan\gamma}\right) \tag{2}$$

$$V = \frac{u}{\cos\delta\cos\beta} = u\left[1+\frac{\tan^2\delta}{\sin^2\gamma}\right]^{\frac{1}{2}} \tag{3}$$

It should be noted that if β is equal to zero, then both devices detect the same angle $\alpha_1=\alpha_2$

2. 2. Geometrical uncertainties

The laser anemometers (LDA or L2F) allowing the direct measurements of the three orthogonal velocity components in a Cartesian set could not be found easily. Chesnakas and Simpson [4] present a three orthogonal-component LDA measuring system to analyse the flow field behind a prolate spheroid. But other LDA systems met in the literature are non-orthogonal ones which means that the angle between the optical axis of the third device and the other two ones differs from a 90 degree angle. This is necessary in turbomachinery where the optical access is limited.

In non orthogonal devices, as shown by the study of Orloff and Snyder [5], the geometrical pattern induces that the third velocity component is coupled with the two other ones, so that systematic errors, especially on the on-axis component, occur in the converting process from

measurement co-ordinates to orthogonal ones. Consequently, the coupling angle should not stay below 30 degrees : yet, most of the actual devices provide 15 degree angles.
The same kind of geometrical limitations occurs with our 3D-L2F anemometer. First of all, a value of 15 degrees was chosen for the angle 2γ in order to allow geometrical access even in narrow gaps, so that α_1 and α_2 are correlated variables. Secondly, uncertainties on α_1 and α_2 ($\Delta\alpha_1$ and $\Delta\alpha_2$) induce uncertainties on α and β which could be estimated by a first order Taylor development of formulas 1 and 2 :

$$(\Delta \alpha, \Delta\beta) = \left[\left(\frac{\Delta \alpha_1 + \Delta \alpha_2}{2}\right), \left(\tan\gamma \ \cos\delta \frac{\Delta \alpha_1 + \Delta \alpha_2}{2\left(\tan^2\gamma + \sin^2\delta\right)}\right)\right]$$

It shows that the higher γ is, the smaller the β uncertainties are, but they also depend on β values themselves. Assuming $\Delta\alpha_1=\Delta\alpha_2$, the magnitude of $\Delta\alpha$ equal the one of $\Delta\alpha_1$ whereas the one of $\Delta\beta$ is 5.7 to 7.6 times $\Delta\alpha_1$ (for β varying from 30 to 0 degrees). It shows that small uncertainties on the α_1 and α_2 mean values induce very large errors on the β one. Similar values could be found in Stauter's paper [6] for a LDA device with a coupling angle of 16 degrees.

3. Statistical Analysis

3. 1. Two-dimensional-L2F data processing

The 3D-L2F technique is based on the 2D-L2F procedure so that it is interesting to call up the two-dimensional data processing which requires two steps.
First, a marginal angular probability density function (p.d.f.) $P_\alpha(\alpha)$ is reached. This p.d.f. allows the calculation of the mean value velocity vector direction, assuming an isotropic turbulence hypothesis :

$$\bar{\alpha} = \int \alpha P_\alpha(\alpha) d\alpha$$

With the associate standard deviation :

$$\sigma^2_\alpha = \int (\alpha - \bar{\alpha})^2 P_\alpha(\alpha) d\alpha$$

Secondly, in orientating the probe volume parallel to the mean velocity direction, a conditional p.d.f. of the velocity modulus $P(u)|_{\bar{\alpha}}$ could be obtained.
Strictly, the total p.d.f. is given by :

$$P_{\alpha,u}(\alpha, u) = P_\alpha(\alpha) P(u)|_\alpha$$

However, if the turbulence is isotropic :

$$P_{\alpha,u}(\alpha, u) = P_\alpha(\alpha) P(u)|_{\bar{\alpha}}$$

Then, any statistical quantities could be determined and especially :

$$\bar{u} = \int uP_{\alpha,u}(\alpha,u)d\alpha du = \int uP_\alpha(\alpha)P(u)|_{\bar{\alpha}} d\alpha du = \int P_\alpha(\alpha)d\alpha \int uP(u)|_{\bar{\alpha}} du = \int uP(u)|_{\bar{\alpha}} du$$

and :

$$\sigma^2_u = \int (u - \bar{u})^2 P(u)|_{\bar{\alpha}} du$$

Nevertheless, this method is a restrictive way of processing the data because of the isotropic turbulence hypothesis.

3. 2. Statistical problems arising with the 3D technique

Previously we have shown that (u, α_1, α_2) can not be obtained simultaneously, so, do not correspond to the same particle. In fact, (u, α_1) and (u, α_2) are determined independently so that $P_{u,\alpha 1,\alpha 2}(u, \alpha_1, \alpha_2)$ is not known. In this context, the only issue to calculate the mean and fluctuating values of the velocity vector is to derive relations between (u, α_1, α_2) and (V, α, β) first and second order momenta. However, information losses resulting from integration process do not allowed an exact calculation. For example, an α variation can be detected as a same direction variation of α_1 and α_2, where a β variation makes α_1 and α_2 varying in opposite ways. The information on direction variations is lost during the integration process for the determination of the standard deviations. As a result, the knowledge of $\sigma_{\alpha 1}$ and $\sigma_{\alpha 2}$ values is not enough to determine σ_α and σ_β because it has become impossible to know if a variation of $\sigma_{\alpha 1}$ and $\sigma_{\alpha 2}$ corresponds to a σ_α or a σ_β variation.

More distinctly the following formula can be derived from relations (1) and (2) :

$$(\alpha_1,\alpha_2) = \left[(\alpha + \arcsin(\tan\beta\tan\gamma)),(\alpha - \arcsin(\tan\beta\tan\gamma))\right] \tag{4}$$

Assuming that $\tan\gamma = \gamma$ (with an error of 0.6 %) and $\tan\beta = \beta$ (with an error of 4 % for β values lower than 20 degrees), formula (4) can be simplified :

$$(\alpha_1,\alpha_2) \simeq (\alpha + \beta\gamma, \alpha - \beta\gamma) \tag{5}$$

By averaging equation (5) :

$$(\bar{\alpha}_1,\bar{\alpha}_2) \simeq \left[(\bar{\alpha} + \bar{\beta}\gamma),(\bar{\alpha} - \bar{\beta}\gamma)\right]$$

Considering α and β variable independence, we get :

$$\sigma_{\alpha_1} = \sigma_{\alpha_2} = \sqrt{\sigma^2_\alpha + \gamma^2\sigma^2_\beta}$$

It shows that only two independent quantities $\sigma_{\alpha 1}$ and σ_u are available to derive the three standard deviations σ_V, σ_α and σ_β. This is due to the fact that α_1 and α_2 are correlated quantities.

Otherwise, because of the small value of γ (7.5 degrees), $\sigma_{\alpha 1}$ and $\sigma_{\alpha 2}$ are more sensible to the α fluctuations than to the β ones. For example, if σ_α and σ_β are equal, the second term of the square root represent 1.7 % of the first one, and if σ_β is three times larger than σ_α , the second term is 15 % of the first one.

3. 3. Isotropic turbulence hypothesis

Deriving relations between (u, α_1, α_2) and (V, α, β) first and second order momenta necessitate a hypothesis of non correlated variables because u, α_1 and α_2 are not measured simultaneously.

Thus, it is interesting to consider an isotropic turbulence model. It is a useful model which is not so far from real flow fields conditions except in boundary layer and other shear flows. However, several authors use this hypothesis even in complex flows. For example Snyder and Orloff [5] consider that the correlation coefficient do not exceed 20 % in shear flows, justifying the use of such a hypothesis. Flack Miner and Beaudoin [7] also corroborate this hypothesis by carrying out measurements in a centrifugal pump and pointing out that Reynolds stresses do not exceed 0.5% even for low flow rates and high turbulence level at various locations.

A three-dimensional stationary isotropic turbulent flow field is described by the fluctuating Cartesian components u_x, u_y, u_z which are considered as independent random variables. The statistical field is defined by the p. d. f. :

$$P_{u_x u_y u_z}(u_x u_y u_z) = P_{u_x}(u_x) P_{u_y}(u_y) P_{u_z}(u_z) = \frac{1}{\sqrt{2\pi}\,\sigma_{u_x}} e^{-\frac{u_x^2}{2\sigma_{u_x}^2}} \frac{1}{\sqrt{2\pi}\,\sigma_{u_y}} e^{-\frac{u_y^2}{2\sigma_{u_y}^2}} \frac{1}{\sqrt{2\pi}\,\sigma_{u_z}} e^{-\frac{u_z^2}{2\sigma_{u_z}^2}}$$

with $\sigma_{u_x} = \sigma_{u_y} = \sigma_{u_z} = \sigma$.

It can be shown that the p. d. f. in spherical co-ordinates become :

$$P_{\xi\theta\varphi}(\xi,\theta,\varphi) = P_\xi(\xi) P_\theta(\theta) P_\varphi(\varphi) = \frac{2\xi^2}{\sqrt{2\pi}\,\sigma^3} e^{-\frac{\xi^2}{2\sigma^2}} \times \frac{\cos\theta}{2} \times \frac{1}{2\pi} = \frac{\xi^2 \cos\theta}{(2\pi)^{\frac{3}{2}} \sigma^3} e^{-\frac{\xi^2}{2\sigma^2}}$$

The convection of this turbulent flow field by a uniform mean velocity gives the resultant flow field (see figure 2) :

$$\vec{V} = \vec{\bar{V}} + \vec{\xi} = (\bar{V} + \xi\cos\theta\cos\varphi)\vec{e}_\xi + \xi\cos\theta\sin\varphi\,\vec{e}_\theta + \xi\sin\theta\vec{e}_\varphi$$

The spherical components of the velocity vector are obtained, assuming a small fluctuation hypothesis and developing the previous formula at the first order :

$$\left[V/\bar{V}, (\alpha-\bar{\alpha}), (\beta-\bar{\beta})\right] \simeq \left[\left(1+\frac{\xi}{\bar{V}}\cos\theta\cos\phi\right), \left(\frac{\xi}{\bar{V}\cos\bar{\beta}}\sin\phi\cos\theta\right), \left(\frac{\xi}{\bar{V}}\sin\theta\right)\right]$$

By means of this relation, it is possible to show that V, α, β are non correlated random variables following the Gaussian law.

$$P_{V\alpha\beta}(V,\alpha,\beta) = \frac{\bar{V}^2\cos\bar{\beta}}{(2\pi)^{\frac{3}{2}}\sigma^3} e^{-\frac{(V-\bar{V})^2}{2\sigma^2}} e^{-\frac{\left(\bar{V}^2\cos^2\bar{\beta}(\alpha-\bar{\alpha})\right)^2}{2\sigma^2}} e^{-\frac{\bar{V}^2(\beta-\bar{\beta})^2}{2\sigma^2}}$$

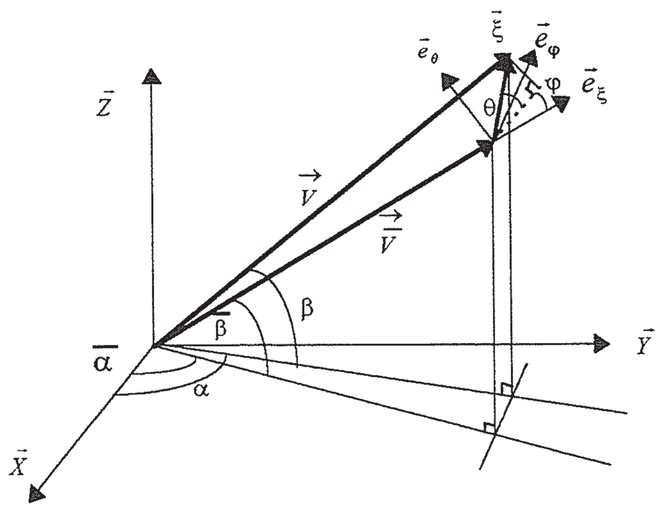


figure 2 : spherical co-ordinates

So that the marginal p. d. f. can be calculated :

$$P_V(V) = \frac{1}{\sqrt{2\pi}\sigma_V} e^{-\frac{(V-\overline{V})^2}{2\sigma_V^2}} \quad with\, \sigma_V = \sigma$$

$$P_\beta(\beta) = \frac{1}{\sqrt{2\pi}\sigma_\beta} e^{-\frac{(\beta-\overline{\beta})^2}{2\sigma_\beta^2}} \quad with\, \sigma_\beta = \frac{\sigma}{\overline{V}}$$

$$P_\alpha(\alpha) = \frac{1}{\sqrt{2\pi}\sigma_\alpha} e^{-\frac{(\alpha-\overline{\alpha})^2}{2\sigma_\alpha^2}} \quad with\, \sigma_\alpha = \frac{\sigma}{\overline{V}\cos\overline{\beta}}$$

For a 2D flow field, using the same hypothesis, it can be shown that polar co-ordinates (u, α) are also Gaussian random variables with σ_α equal to $\sigma/\overline{u}$ and σ_u equal to σ. Experimentally, we verify that σ_α is actually equal to $\sigma_u/\overline{u}$ and that the velocity modulus and direction distributions look like the Gaussian distributions of the same mean value and standard deviation.
Those remarks corroborate the isotropic hypothesis and we will use it to calculate mean values and standard deviations of the spherical components (V, α, β) in the following.

3. 4. Mean value calculations

First of all, it should be noted that (u, α_1, α_2) are correlated variables whereas (V, α, β) or (V, α, δ) are non correlated ones.

3. 4. 1. $\overline{\alpha}$ calculation

Equation (1) leads to :

$$\overline{\alpha} = \frac{\overline{\alpha}_1 + \overline{\alpha}_2}{2}$$

3. 4. 2. $\overline{\beta}$ estimation

The direct integration of equation (2) is not easy because of the non-linearity. Then a second order Taylor development of equation (2) around the mean values of u, α_1, α_2 is performed, assuming that $\sin\delta \sim \delta$ and $\tan\gamma \sim \gamma$, so that the β mean value can be expressed as followed :

$$\overline{\beta} = \arctan\left[\frac{\sin\overline{\delta}}{\tan\gamma}\right] - \frac{\gamma^3\overline{\delta}}{\left(\gamma^2+\overline{\delta}^2\right)^2}\sigma^2_\beta$$

The second term of the relation is very small even for very penalising configurations. For example, if the β value is equal to 30 degrees and σ_β to 11.5 degrees, its value is 0.74 degrees. Thus a zero order Taylor development should be considered satisfactory.

3. 4. 3. Estimation of $\overline{V}$

Using equation (3) and developing the same calculation as the β one, we get :

$$\overline{V} = \overline{u}\left[1+\frac{\tan^2\overline{\delta}}{\sin^2\gamma}\right]^{\frac{1}{2}}\left[1+\frac{\gamma^4}{2\left(\gamma^2+\overline{\delta}^2\right)^2}\sigma^2_\beta\right]$$

Here we could also limit the Taylor development to order zero, the second term of the relation being about 0.01 for the previous conditions.

3. 5. Fluctuation value estimations

As it has been shown previously in paragraph 3. 2, a direct calculation of V, α, β second order momenta is impossible. However, the isotropic turbulence hypothesis induce the following relations between σ_α, σ_β and σ_V :

$$\sigma_\alpha = \frac{\sigma_V}{\overline{V}\cos\overline{\beta}} = \frac{\sigma_\beta}{\cos\overline{\beta}}$$

Moreover equation (5) induces that :

$$\sigma_{\alpha_1} = \sigma_{\alpha_2} = \sqrt{\sigma_\alpha{}^2 + \gamma^2\sigma_\beta{}^2}$$

So that :

$$\sigma_{\alpha_1} = \sigma_{\alpha_2} = \sqrt{\sigma_\alpha{}^2 + \gamma^2\cos^2\overline{\beta}\sigma_\alpha{}^2} = \sigma_\alpha\sqrt{1+\gamma^2\cos^2\overline{\beta}}$$

Hence, we get :

$$\begin{cases} \sigma_\alpha = \dfrac{\sigma_{\alpha_1}}{\sqrt{1+\gamma^2\cos^2\overline{\beta}}} \\ \sigma_\beta = \dfrac{\sigma_{\alpha_1}\cos\overline{\beta}}{\sqrt{1+\gamma^2\cos^2\overline{\beta}}} \\ \sigma_V = \dfrac{\sigma_{\alpha_1}\overline{V}\cos\overline{\beta}}{\sqrt{1+\gamma^2\cos^2\overline{\beta}}} \end{cases}$$

If we now look for the Cartesian components of the fluctuating flow field, we should make a Reynolds development of all the instantaneous components which could be split up into a mean and a fluctuating value. This leads to :

$$\begin{cases} \overline{U}_x + u_x = (\overline{V}+v)\cos(\overline{\beta}+\beta')\cos(\overline{\alpha}+\alpha') \\ \overline{U}_y + u_y = (\overline{V}+v)\cos(\overline{\beta}+\beta')\sin(\overline{\alpha}+\alpha') \\ \overline{U}_z + u_z = (\overline{V}+v)\sin(\overline{\beta}+\beta') \end{cases}$$

Hence, if we assume that the fluctuations are small compared to the mean values :

$$\begin{cases} \cos\beta' \approx \cos\alpha' \approx 1 \\ \sin\alpha' \approx \alpha' \\ \sin\beta' \approx \beta' \end{cases}$$

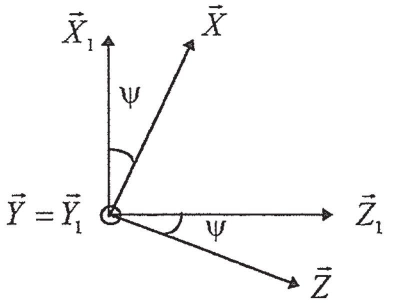
And, if we do not take into account the second order terms, we get :

$$\begin{cases} u_x = -\overline{V}\cos\overline{\beta}\sin\overline{\alpha}\alpha' - \overline{V}\sin\overline{\beta}\cos\overline{\alpha}\beta' + v'\cos\overline{\beta}\cos\overline{\alpha} \\ u_y = \overline{V}\cos\overline{\beta}\cos\overline{\alpha}\alpha' - \overline{V}\sin\overline{\beta}\sin\overline{\alpha}\beta' + v'\cos\overline{\beta}\sin\overline{\alpha} \\ u_z = \overline{V}\cos\overline{\beta}\beta' + v'\sin\overline{\beta} \end{cases}$$

If we now take the square and the average of those three relations, assuming that v, α', β' are independent variables so that correlation coefficients between those variables are zero, we get the values of the three standard deviations in the Cartesian co-ordinates :

$$\begin{cases} \sigma_{u_x} = \sqrt{\overline{V}^2 \cos^2\overline{\beta}\ \sin^2\overline{\alpha}\sigma_\alpha{}^2 + \overline{V}^2 \sin^2\overline{\beta}\ \cos^2\overline{\alpha}\sigma_\beta{}^2 + \sigma_V{}^2 \cos^2\overline{\beta}\ \cos^2\overline{\alpha}} \\ \sigma_{u_y} = \sqrt{\overline{V}^2 \cos^2\overline{\beta}\ \cos^2\overline{\alpha}\sigma_\alpha + \overline{V}^2 \sin^2\overline{\beta}\ \sin^2\overline{\alpha}\sigma_\beta + \sigma_V \cos^2\overline{\beta}\ \sin^2\overline{\alpha}} \\ \sigma_{u_z} = \sqrt{\overline{V}^2 \cos^2\overline{\beta}\sigma_\beta + \sigma_V \sin^2\overline{\beta}} \end{cases}$$

Moreover, should the results be given in a different Cartesian set $(\vec{X}_1, \vec{Y}_1, \vec{Z}_1)$, the new standard deviations could be calculated as follows :



$$\begin{cases} U_{x_1} = U_x \cos\psi - U_z \sin\psi \\ U_{y_1} = U_y \\ U_{z_1} = U_x \sin\psi + U_z \cos\psi \end{cases}$$

With the same procedure as before, the fluctuating flow field can be obtained :

$$\begin{cases} u_{x_1} = u_x \cos\psi - u_z \sin\psi \\ u_{y_1} = u_y \\ u_{z_1} = u_x \sin\psi + u_z \cos\psi \end{cases}$$

So, assuming that $\overline{u_x u_z}$ could be neglected, the standard deviations are :

$$\begin{cases} \sigma_{x_1} = \sqrt{\sigma^2{}_x \cos^2\psi + \sigma_z{}^2 \sin^2\psi} \\ \sigma_{y_1} = \sigma_y \\ \sigma_{z_1} = \sqrt{\sigma_x{}^2 \sin^2\psi + \sigma_z{}^2 \cos^2\psi} \end{cases}$$

4. Check of the measurement technique in an axisymmetrical free jet

4. 1. Introduction

A preliminary test has been carried out in an axisymmetrical free jet to verify the statistical method efficiency.

This experimental set-up has been chosen for several reasons. First of all, a characterization of our wind tunnel has been made possible because of the various results existing in the literature (Wygnanski and Fiedler [8], Corrsin [9]). Secondly, we could make the turbulence intensity vary : from 2% in the potential core to 50% in the developed flow region. Thirdly, a lot of measuring problems are present in this configuration : in the potential core boundary area because of the eddy pattern, the high gradients and the seeding difficulties, and in the developed flow region where the turbulence levels are very high. In this chapter, the experimental set-up will be describe first, followed by an analysis of the results obtained with different measuring devices.

4. 2. Experimental facility

We use a 20 mm diameter wind tunnel which allows a vertical development of the free jet. The velocity at the nozzle exit can vary and a static pressure probe gives the velocity value within an uncertainty band of 0.5%. In order to protect the hot wire probe and because of stability problems, the value of the exit velocity should stay between 40 and 65 m/s.

4. 3. Instrumentation

The 3D-L2F anemometer consists of an Argon-laser operating in multicolour mode, coupled with an optical head manufactured by Polytec. The four different distances existing between the start and the stop of our two 2D-devices permit the adjustment of the beam separation with the degree of turbulence of the flow (Schodl [10]).
Electronic and acquisition systems are identical to the 2D-ones previously developed in the L.M.F.A. at E.C.L [11]. All acquiring and processing procedures have been fitted to the 3D technique.
The anemometer has been calibrated in order to precisely characterize the geometrical set up of the probe volume (especially the exact value of angle γ).
Laser measurements have been compared to those obtained with conventional probes : the mean values have been measured with a Pitot probe and the fluctuating ones with a crossed hot wire probe.

4. 4. Results

Measurements with the laser anemometer, the hot wire probe and the Pitot tube have been carried out in three sections downstream the nozzle exit, orthogonal to the jet axis as shown in figure 4. The first plane is located in the potential core, whereas the second and the third ones are in the fully developed flow area. The free jet characteristics are presented in the following table:

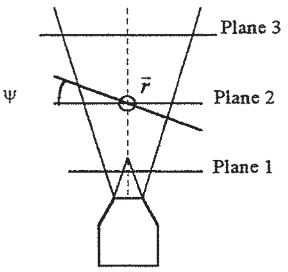


figure 4 : Measurement planes

	Plane 1	Plane 2	Plane 3
distance from the nozzle (⌀)	2	10	20
jet diameter(mm)	40	80	120
u_{rms}/U_m (%)*	2	15	25
U_m (m/s)*	40	50	25

* Jet axis mean velocities and turbulence level.

Furthermore, for each measurement plane, four different angles ψ between the plane perpendicular to the jet axis and the optical axis of the 3D-device are tested in order to simulate 3D flow effects (0; 7.5; 15 and 30 degrees). The results are shown on figures 5 to 18.

4. 5. Analysis

On figures 5, 6 and 7 it can be seen that the mean longitudinal velocity profiles (U) are well determined whatever the value of the angle ψ is. However, in planes 2 and 3, where the turbulent intensity exceeds 20%, U is slightly overestimated.
Because of the difficulty in estimating the mean radial velocity (V) with a hot wire, Wygnanski and Fiedler [8] had to derive its value from the continuity equation. The obtained pattern are very similar to those observed from laser measurements on figures 8, 9 and 10.
The mean tangential velocity component (W) should be zero, but a mean value of 1.5 m/s with a large discrepancy can be seen on figures 11 and 12. This corresponds to an error of 2 degrees

on the β estimation which is correlated to small errors on the mean values of α_1 and α_2 of less than 0.2 degrees. We observe that the dispersion of the results tends to increase with the value of ψ and with the turbulence level.
For plane 1 (see figures 13 and 14), we observe a good agreement between the hot wire and the laser measurements for longitudinal and radial fluctuations, regardless of the value of the angle ψ. The pictures show only some differences near the boundaries of the jet, which can be explained by the different behaviour of the two measuring devices in this intermittence area of shear flow. For plane 3 (see figures 15 and 16), the results are also satisfactory, and we can see that the orientation of the optical axis does not influence the measurements in this developed flow area. However, longitudinal laser values are underestimated and radial ones are overestimated. Moreover, a larger dispersion than that observed in plane 1 can be seen : this can be related to the high turbulence level exceeding 25 % in this region.
If we now look at the tangential fluctuations for plane 1 and 3 (see figures 17 and 18), and if we compare the laser results to the radial fluctuations measured with the hot wire probe (assuming as Wygnanski and Fiedler that the radial and the tangential fluctuations are equal), then we see that the results are satisfactory whatever the value of ψ is. However, the turbulence intensity level influences the laser measurements in plane 3.

5. Conclusion

It has been shown that measurements of strong 3D flow phenomena are allowed by the 3D anemometer with a rather good accuracy. The results are satisfactory even for high turbulence levels (up to 50%). Consequently, the device is expected to allow measurements in complex flows like those encountered in the wakes, at the leading edge, in the vicinity of the corner vortex and in the tip clearance of real turbomachines. The next step of this study is to perform measurements in a low-speed high-loaded compressor rotor.

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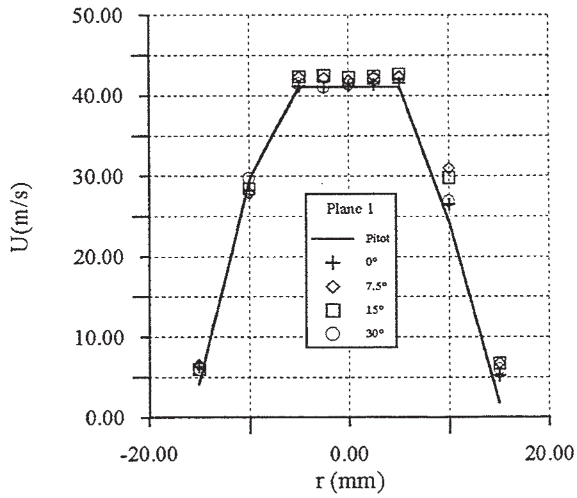

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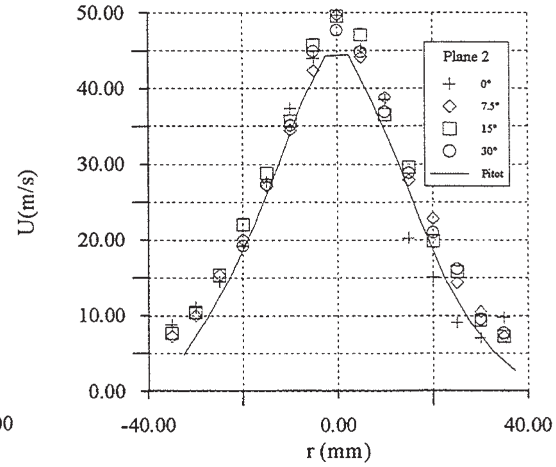

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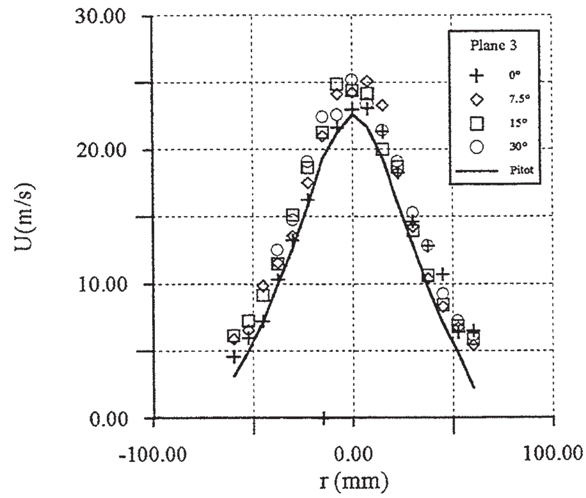

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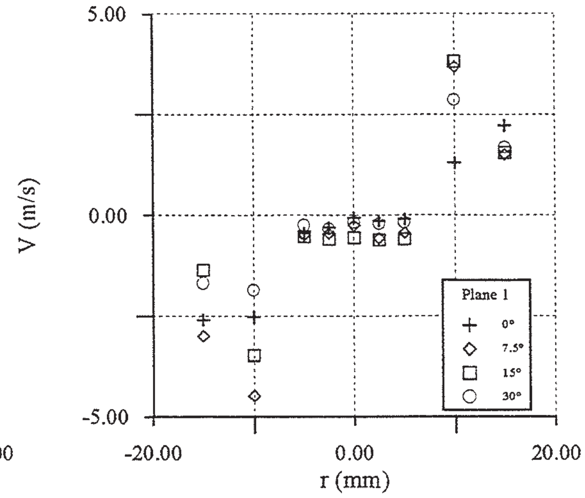

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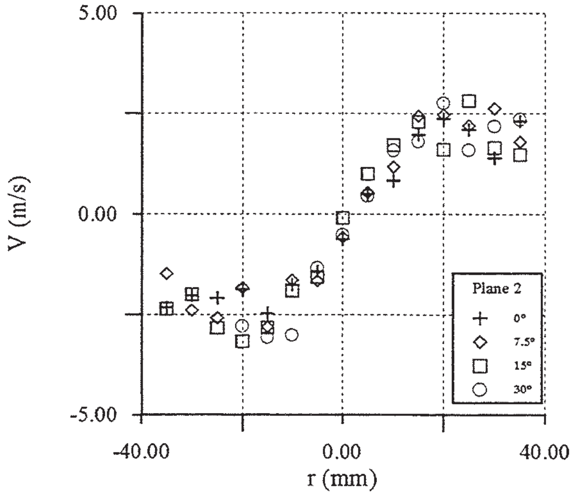

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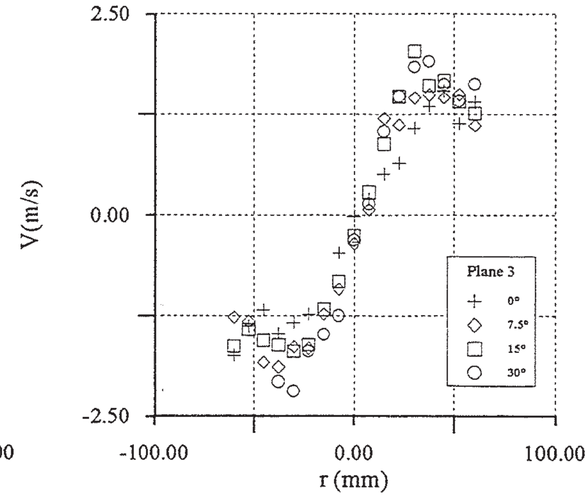

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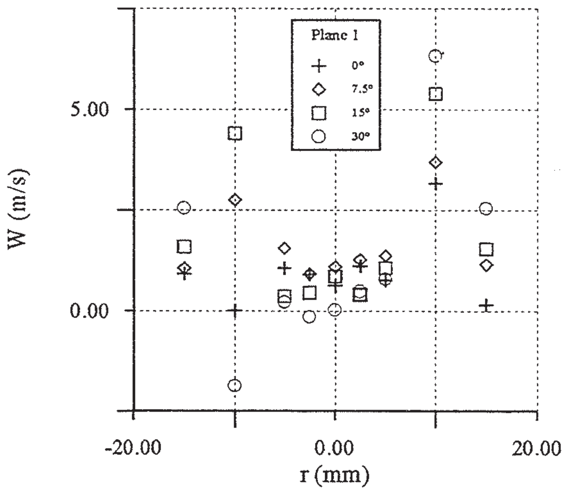

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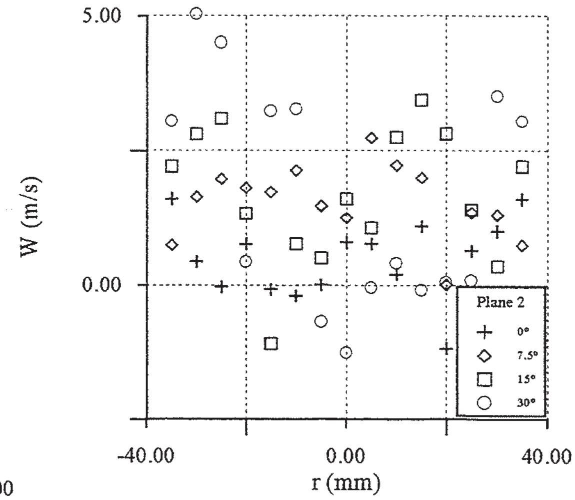

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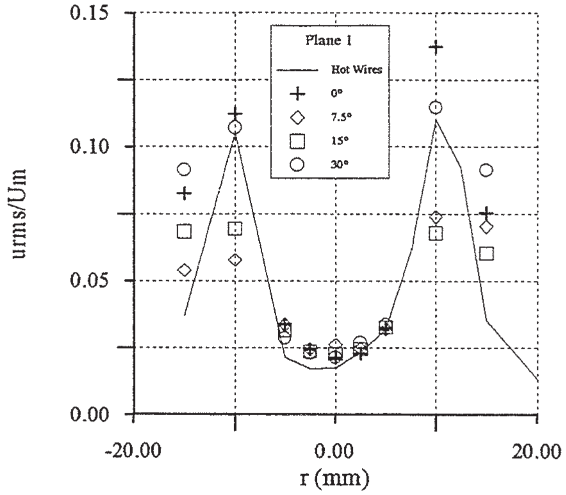

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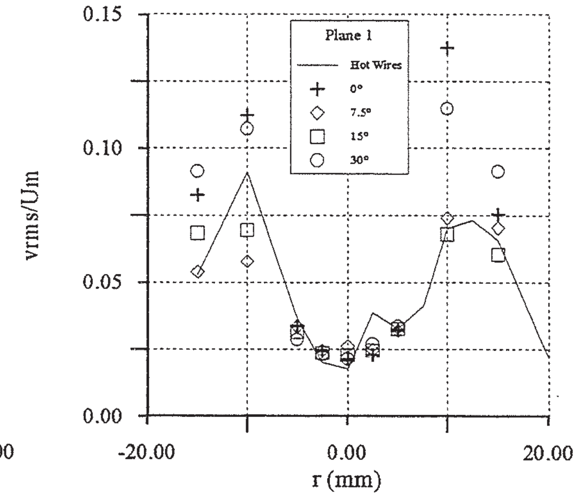

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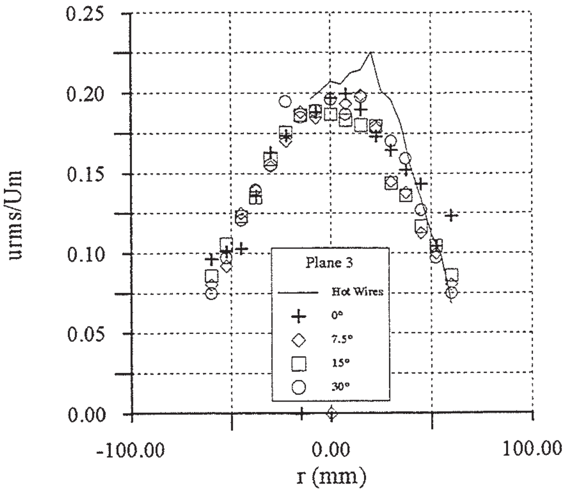

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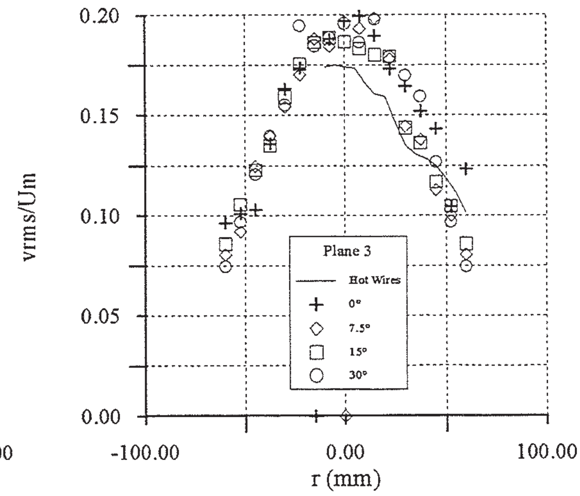

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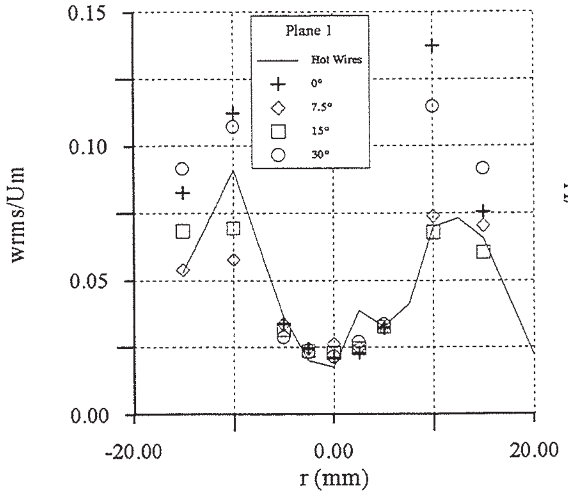

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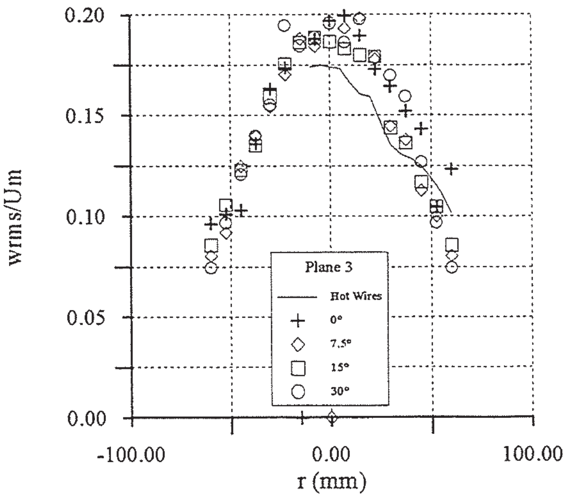

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