A 3D LDA TECHNIQUE FOR THE MEASUREMENT OF TURBULENT QUANTITIES IN COMPLEX TURBOMACHINERY FLOWS. DEMONSTRATION IN AN AXISYMMETRIC FREE JET

G. Simeonides, V. Zaphirakis, K. Mathioudakis
Lab of Thermal Turbomachines ,
National Technical University of Athens
P.O. Box 64069, 15710 Zografou, Athens, Greece

Keywords: *Laser Doppler Anemometry, turbulence, shear stresses, jet flow, turbomachinery*

Abstract

In the present paper a study for improving a 3D measurement technique using Laser Dopler Anemometry (LDA) is presented. A 3D LDA system developed for measurements in turbomachinery components is used for the investigation. The sensitivity of the measurement procedure on small errors in aligning the laser optics is demonstrated and it is shown that by using an improved alignment method it is possible to improve the accuracy of the measurements. The effect of coincidence window size on data rates during the experiments is also studied. Measurement data obtained on a free jet configuration are used to demostrate that the measurement procedure presented can be used to obtain sound mean flow velocity and turbulence data.

1. INTRODUCTION

Three-dimensional laser Doppler anemometry is widely used in the measurement of complex turbulent turbomachinery flows. In general, 3D LDA systems are developed to the point of providing accurate (3D, three-component) mean velocity fields and, to a lesser extent normal stress (RMS of individual component fluctuations) distributions [1-5]. The measurement of shear stress distributions (cross-correlations of fluctuating components), however, requires the simultaneous measurement of individual instantaneous components [6] or, at least, their measurement within a pre-specified time coincidence window. This window should be small relative to the time scales of the measured turbulent flow (typically, for flow velocities of the order of 100 m/s and large turbulent length scales of the order of 10 mm, the imposed time coincidence windows should be less than 10 μs, in order to capture the transport of turbulent length scales 1/10th the scale of large eddies).

Furthermore, turbomachinery applications impose severe optical access restrictions, which do not allow the direct measurement of three orthogonal velocity components; instead, two independent orthogonal components are measured together with a third dependent component inclined at a small angle to the orthogonal ones. The transformation required to estimate even the mean of the third orthogonal velocity component, then causes a strong amplification of measurement errors, which increases dramatically at included angles of less than 30° (that are typical of turbomachinery applications), particularly if the three measured components are not synchronized and, thus, uncorrelated [7,8]. Such induced errors are further amplified by modest spatial misalignment between the directly measured components, especially in regions of strong velocity gradients, as demonstrated below.

Determination of the normal stress (RMS) of the third (indirectly measured) orthogonal velocity component, requires time-synchronous measure-ments, because it also depends on the cross-correlation of the fluctuations of the two non-orthogonal components from which it is determined. Of course, a similar time coincidence/ synchronization requirement is imposed for the estimation of instantaneous values of the third orthogonal velocity component.

The performance of accurate three-dimensional measurements of the mean velocity field as well as the normal and shear stresses in turbomachinery components, therefore, imposes stringent requirements for temporal and spatial coincidence of the measured components, in addition to the need for high quality signals and strong SNR's. Notably, the imposition of small temporal coincidence windows tends to reduce substantially the acquisition data rates, often making measurements impractical or even impossible; in this respect, ensuring spatial coincidence (alignment) does ameliorate the situation also in terms of temporal coincidence.

The purpose of the present paper is to discuss the difficulties encountered with the implementation of the 3D LDA system of the Lab of Thermal Turbomachines , National Technical University of Athens(LTT/NTUA), in turbomachinery measure-ments, focusing on the issues of spatial and temporal coincidence of the three directly measured velocity components, to outline the necessary remedies, and to demonstrate the resulting improvements and their adequacy. A set of data taken in a developing turbulent free jet is used as a validation test case.

2. THE 3D LDA SYSTEM, ITS CALIBRATION AND APPLICATION

The 3D fiber-optics LDA system of the LTT/NTUA comprises a 2D optical probe, powered by a 5-watt argon-ion laser, that makes use of the green and blue beams to measure two orthogonal velocity components, and a 1D probe, powered by an infrared laser-diode, that measures the third non-orthogonal velocity component. This third velocity component is measured in the plane of the green beam pair. The layout of the system is shown in Figure 1.

The system is intended for measurements in turbomachinery components with limited optical access. The angle between the two probes is thus limited to between 20 and 40 degrees, depending on the allowed separation between the two probes and the focal length requirements for the lenses. The system has been previously successfully employed for the measurement of mean velocity distributions in complex high-speed 3D turbomachinery flows, while some data on the RMS fluctuations of individual components have also been acquired [5,9].

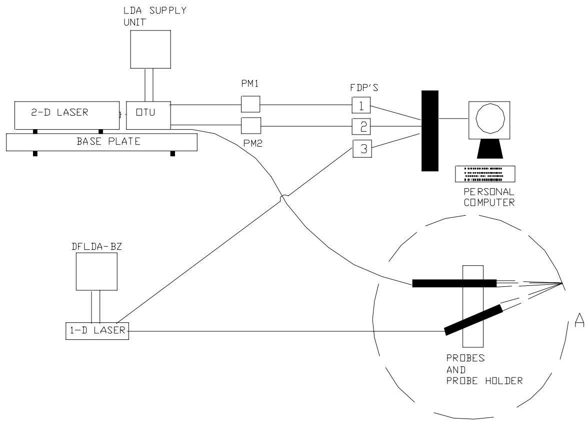


Figure 1: Layout of the three component LDA system.

The placement of the system for measurements on an annular compressor cascade is shown in Figure 2, with the angle between the two probes typically set to 23 degrees. Despite the successful application for the mean values and the RMS of the directly measured components, difficulties have been encountered in the determination of the RMS fluctuation of the third (indirectly measured) component, as well as of cross-correlations of

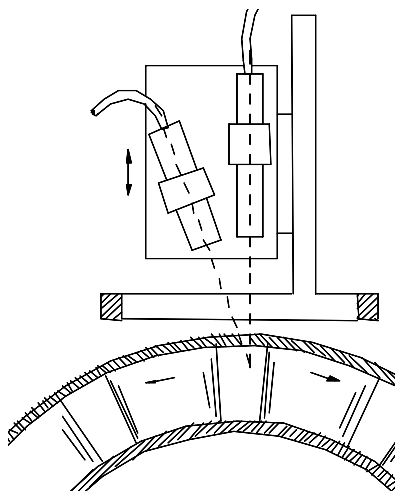


Figure 2: Optical probes placement for measurement of 3D flow in an annular cascade.

the form of Reynolds stresses. They arise from the fact that derivation of these components requires the simultaneous measurement of all three velocity components, which in practical terms means that they should all be measured within a pre-specified small coincidence time-window. A small window, however, caused unacceptably low data acquisition rates, making the measurement of these quantities difficult. Thus the stimulus for the present study.

In order to assess the measuring capabilities of the system a series of 3-D measurements have been performed in a small free-jet with a 20 mm nozzle exit diameter (D). The working fluid was air. The maximum centre-line axial mean velocity was about 100 m/sec with a low turbulence intensity (about 1% at the nozzle exit), corresponding to a Reynolds number of $1.33 \cdot 10^5$.

Traverses normal to the jet axis have been made at different locations downstream of the jet exit. Measurements were performed by positioning the measurement system at different orientations, the usual one however being to measure the axial and peripheral components directly by the green and blue pairs of beams, and to deduce the radial component by combining the third inclined infrared beam data to one of the directly measured orthogonal components.

3. PRELIMINARY LDA SETUP AND CALIBRATION IN THE FREE JET - IDENTIFICATION OF PROBLEMS

3.1 Laser beam alignment

In the original experimental set-up, alignment of the six laser beams and, thus, spatial coincidence of the three probe volumes was achieved with the aid of a small, highly reflective sphere, centered at the focal point of the six laser beams / measurement volume. Ensuring that the reflection of each of the six laser beams was returning to its point of emission would, then, imply that each beam impinges normal to the surface of the sphere and, consequently, guarantee that all six beams are focused to the center of the sphere which would coincide with the center of the measurement volume.

3.2 Data rates

The individual channel data rates attained with the LDA system lie in the vicinity of 800 samples/s for the green and blue beam channels, and of 400 samples/s for the weaker infrared beam channel. In the original measurement configuration, with the aforementioned beam alignment procedure, three-component coincident measurements were virtually impossible (at least for coincidence windows smaller than 100 μs), with data rates dropping effectively to zero.

Figure 3 presents the data rates attained for different measurement configurations. Even the imposition of two-component time coincidence in the original measurement configuration (open circle symbols) is seen to have caused a rapid deterioration of the attainable data rate from the individual component limit (400 samples/s for the IR beams, in this case) to as little as 2 samples/s for a 10 μs coincidence window.

This enormous reduction in data rate under the constraint of two- or three-component time coincidence (making measurements practically impossible) has been attributed to two primary causes:

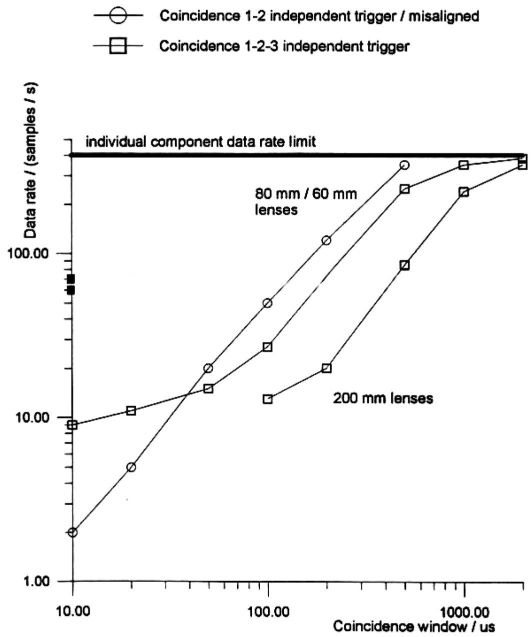


Figure 3: Data rates attained with 2 and 3 component coincident measurements

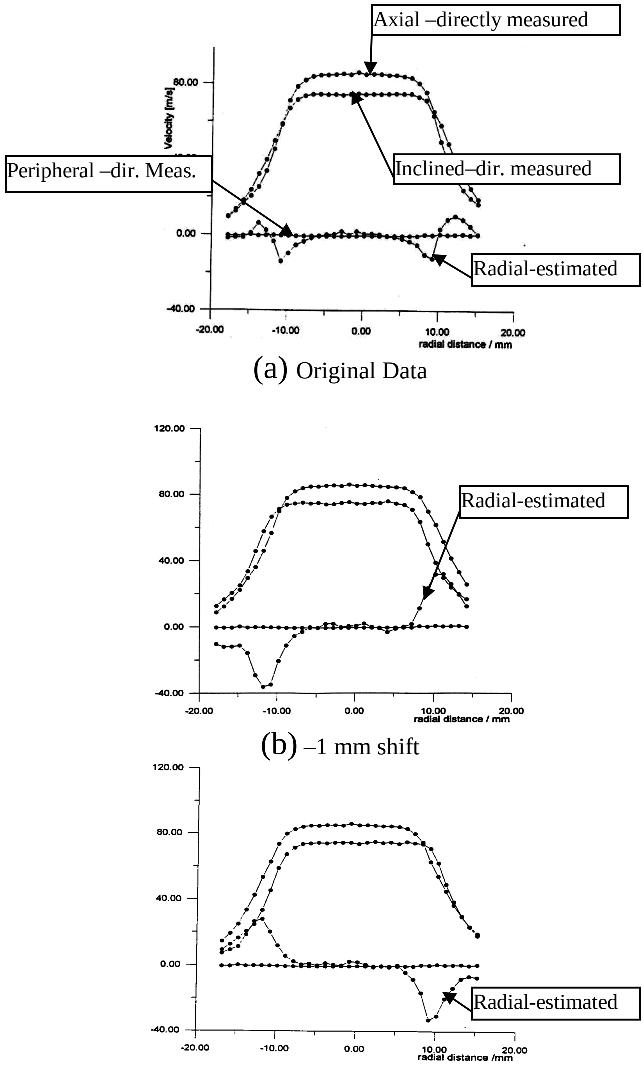
- an inadequate alignment of the six laser beams (and three measurement volumes) by the procedure of section 3.1, and
- the lack of synchronization of the three data acquisition channels (one for each component), in particular of the trigger of the three frequency domain processors used.

3.3 Free jet calibration - manifestation of inadequate spatial and temporal coincidence of the three components

The 3D LDA system, aligned as described above, has been tested/calibrated in the axisymmetric free jet facility described in section 2. The orthogonal green and blue beams have been used for the direct measurement of the axial and circumferential velocity components, while the infrared beams have measured an inclined velocity component (at 23^o to the axial direction). The radial velocity component has then been estimated from the combination of the axial and inclined velocity components, by applying the appropriate trigonometric relations [10].

The three directly measured plus one (radial) estimated velocity components on the jet flow are shown in Figure 4a. All three directly measured mean velocity profiles exhibit (at least, qualitatively) the expected behaviour. The estimated mean radial velocity profile, however, appears symmetric about the jet axis (which corresponds to outflow on one side of the jet and inflow on the other side) in marked contradiction to the expected anti-symmetry of the profile (i.e. axisymmetric outflow or inflow around the jet periphery).

Now, if in the post processing estimation of the mean radial velocity profile it is assumed that the inclined velocity measurement is offset in the transverse direction by as little as 1 mm relative to the axial velocity measurement (compared to a jet exit diameter of 20 mm and, more importantly, to a typical optical depth of the each probe volume of the order of 1-2 mm), the resulting profile is dramatically modified in the high gradient region at the periphery of the jet, as illustrated in Figs. 4b, c.



(a) Original Data

(b) –1 mm shift

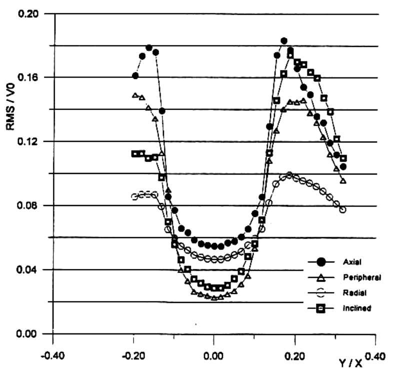
(c) +1 mm Shift

Figure 4: Typical free jet mean velocity profiles – original measurement configuration with inadequate probe volume alignment

This result demonstrates the extreme importance of accurate spatial alignment of the three probe volumes, especially in regions of high velocity gradients, even if we are only interested in the measurement of mean velocity distributions and discard the estimation of turbulence quantities. In effect, the laser beam alignment procedure of section 3.1 is, hereby, rendered inadequate even for mean velocity measurements in high velocity gradient regions.

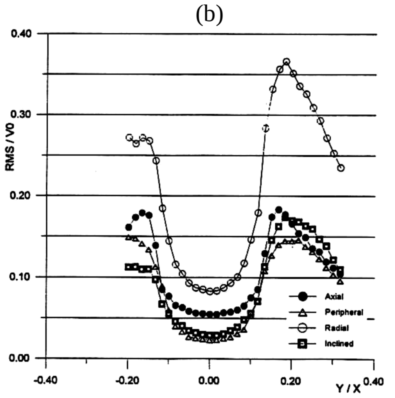
In addition, the above data have been acquired in a non-time-coincident mode (because of the very low data rates discussed in section 3.2). Consequently, the mean and RMS (normal stress) profiles of the radial velocity component have been estimated from the mean and RMS profiles of the (directly measured) axial and inclined velocity components [10], while the determination of shear stresses was not possible because of the lack of synchronization of the cross-correlated components.

The important effect of the lack of time-coincidence in the measurements is illustrated in Figure 5 by comparison of the radial velocity RMS profiles estimated either (approximately) from the RMS of the axial and inclined components or from the time series of instantaneous radial velocity data (incorrectly estimated, due to the lack of synchronization of the axial and inclined components, from the combination of instantaneous measurements of the axial and inclined components at each point [10]).



(a) derived from RMS values

(b)



(b)derived from time series

Figure 5: Typical normalized free jet RMS velocity fluctuation profiles – original measurement configuration with inadequate spatial and temporal coincidence

4. Coincidence Enhancement, Improvement In Data Rates

4.1 Improved laser beam alignment

Having demonstrated the shortcomings of the original beam alignment method in section 3, and bearing on the findings of [11] as to the extreme importance of warranting a common finite measurement volume for the three velocity components, a new beam alignment procedure has been established as follows.

A 40X magnification microscope objective lens is first employed to focus all probe volumes onto a single spot. Thereafter, a 25 μm pinhole is placed at the center of the desired measurement volume, and all six laser beams are fine-tuned so as to maximize the throughput of each of them through the pinhole. The receiving optics are also aligned in a similar manner to the same degree of accuracy. Notably, the 25 μm pinhole compares to individual laser beam diameters in the range between 20 μm and 85 μm, depending on the lenses used on the emitting optics.

Moreover, it is of paramount importance to maintain the stringent tolerances in laser beam alignment throughout an experiment or cycle of experiments, stressing the need for extremely robust optical benches. In our subsequent experiments, all six laser beams were found to maintain their alignment through a series of typical experiments, after the fairly cumbersome alignment procedure outlined above (see also [12] for difficulties in establishing and maintaining spatial coincidence).

4.2 Synchronization of data acquisition channels

Having attained the necessary degree of spatial coincidence of the three individual probe volumes (i.e. obtained a common finite measurement volume), steps had to be taken to ensure that all three channels measure simultaneously the instantaneous velocity components of the same particle at a given point. This required synchronization of the three data acquisition channels and, specifically, synchronization of the triggers of the three frequency domain processors (FDP's).

Synchronization was achieved by operating the FDP's in a master-slave configuration with the master unit providing the trigger also to the two slave units. It is worth noting that the implementation of this straightforward intervention on the data acquisition hardware revealed that attention must be taken as to the selection of the master channel. In particular, the three probe volumes (although properly aligned) do not coincide fully and also have different size because of the different beam diameters and different lenses of the emitting optics. Consequently, it was found practical to set the master trigger on the channel with the smallest probe volume, while the inverse could yield excessively low signal validation rates on the slave channels.

4.3 Data rate improvement

Returning to Fig. 3, the improved beam alignment procedure has resulted in the attainment of reasonable data rates for three-component coincident measurements, even without synchronization of the data acquisition hardware. The data rate dependence on the coincidence window (for independent operation / triggering of each data acquisition channel) is seen to be upper bound by the lowest individual component data rate (at 400 samples/s for the infrared laser beams) for large coincidence windows, while it drops to about 10 samples/s for coincidence windows of 10 μs (compared to the 2 samples/s that was attained with the original alignment for only two-component coincidence).

Evidently, at small coincidence windows a significant improvement in the data rate is achieved through the synchronization of the frequency domain processors in a master-slave configuration. With reference to Fig. 3, the achieved three-component coincidence data rate lies between 60 and 70 samples/s, i.e. about 15% of the limiting individual component data rate (of 400 samples/s) which corresponds closely to the ratio of the common measurement volume to the individual component probe volume. It is only in this case of synchronized data acquisition that the simultaneous measurement of the three velocity components of the same particle at the same point (in the common measurement volume) is assured, provided of course that the seeding rate is not excessively high (ensuring the presence of - statistically - one single particle in the measurement volume at a time).

5. EVALUATION OF THE IMPROVED MEASUREMENT CHAIN IN THE FREE JET

Following the implementation of the aforementioned improvements in the measurement technique (concerning spatial and temporal coincidence of the three measured velocity components, and the achieved validated data rates), the 3D LDA system was set up in a typical configuration for turbomachinery measurements and data were collected in the calibration free jet described in section 2, at axial stations between 1 and 9 jet exit diameters from the jet exit [10]. A selection of the results are given herebelow in comparison with similar data from the literature to substantiate the validation as well as the residual limitations of the technique.

5.1 Comparison of mean and fluctuation velocity profiles

A typical profile of the (directly measured) axial mean velocity component, 1 jet exit diameter from jet exit, is compared to the data of [14] in Fig. 6, which demonstrates an adequate spatial resolution in the high gradient region at the circumference of the jet. The peripheral component remained zero within the measurement accuracy of 0.5 m/s throughout the jet. Of particular interest was the result for the mean radial velocity profile.

Fig. 7 shows a very good comparison between a directly measured radial velocity profile and one estimated from the combination of coincident measurements of the axial and inclined (at 23 degrees) velocity components. The form of and agreement between the profiles of Fig. 7 demonstrates that the problem of Fig. 4 (caused by inadequate spatial alignment) have been eliminated. A measured radial mean velocity profile is compared to the data of [14] in Fig. 8.

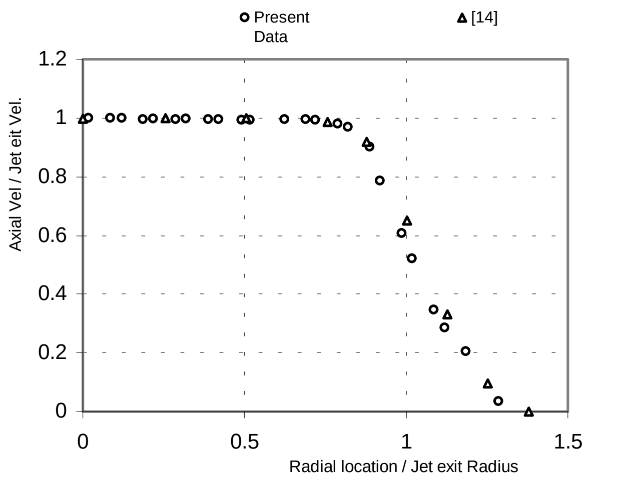


Figure 6: Comparison of mean axial velocity profile with data from literature

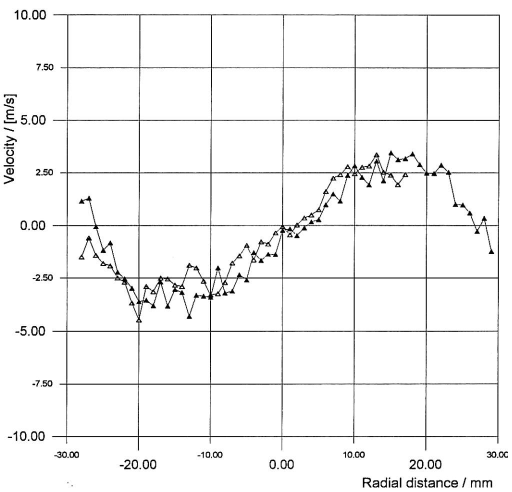


Figure 7: Mean radial velocity distribution, 6 diameters from exit. Directly measured and estimated values.

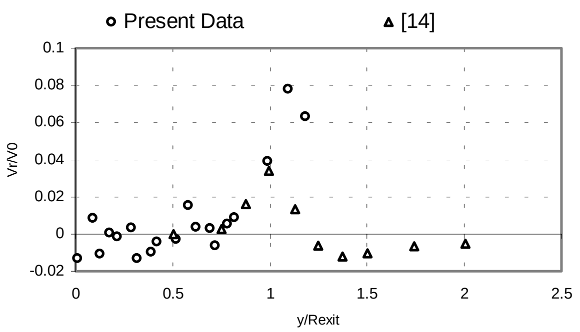


Figure 8: Mean radial velocity profiles. Comparison to data from literature.

The directly measured profile of the RMS fluctuation of the axial velocity component is compared to measurements by a hot wire anemometer and the data of [14] in Fig. 9. The discrepancy between the present LDA and hot wire data and the data of [14], exhibiting a 2% maximum on the centerline and fading out towards the periphery of the jet, is explained by the presence of a forced fluctuation induced by the jet blower that was evaluated from the spectral analysis of the hot wire data [10]. The modest axial shift between the LDA and hot-wire data is also noted, which explains the small discrepancy near the jet axis.

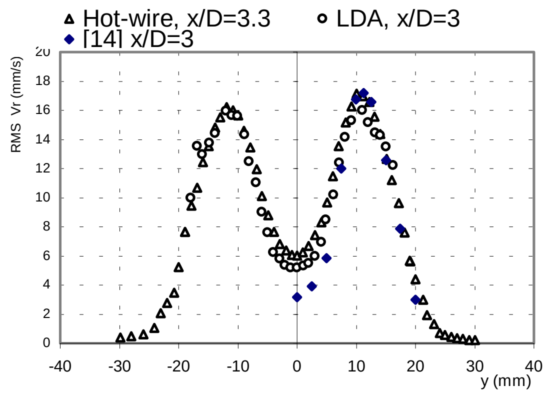
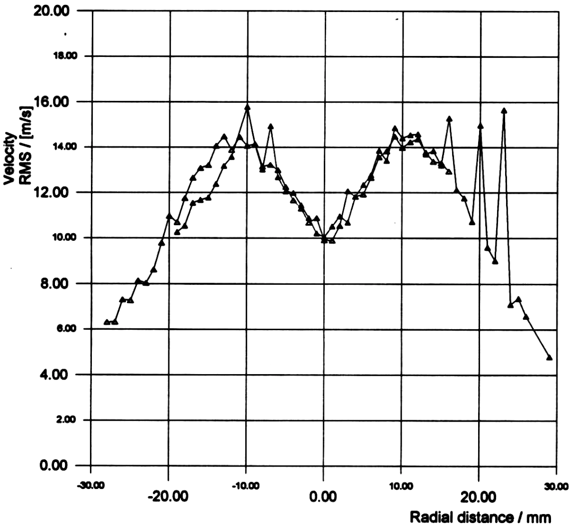


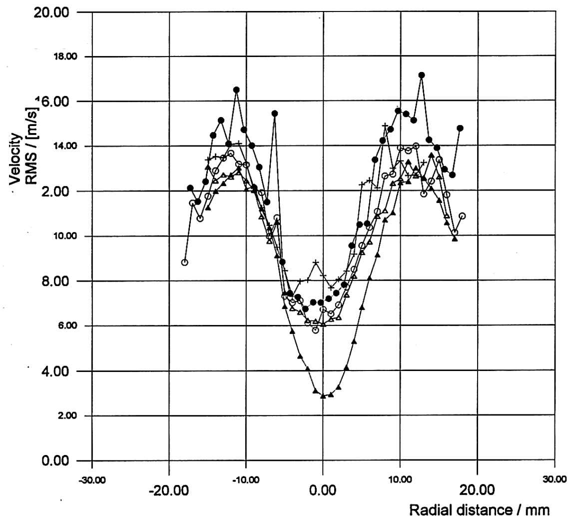
Figure 9: Comparison of axial RMS velocity fluctuation measured by LDA and hot-wire with the data of [14].

Comparisons between directly measured and estimated (from the combination of axial and inclined component data) RMS fluctuation profiles were made for the peripheral and radial velocity components. Typical results are shown in Fig. 10 for two axial stations, one at three jet exit diameters and one at six diameters from jet exit.

With reference to Fig. 10a good agreement is found between the directly and estimated RMS velocity fluctuation profiles (of the peripheral velocity component in this case). At the upstream station of Fig. 10b, however, which exhibits a lower turbulence level in the jet core, a significant discrepancy is observed in the central part of the jet, whereby the indirectly estimated profiles exhibit a minimum RMS of the order of 6% of the jet exit velocity. This level of turbulence appears to be a threshold value for the indirectly measured component caused by a significant amplification of measurement errors through the estimation procedure that is connected to the small included angle between the axial and inclined components that are directly measured.



(a) peripheral component RMS, x/D=6



(b) radial component RMS, x/D=3

Figure 10: Comparison of directly measured and estimated peripheral and radial RMS velocity fluctuations.

On the contrary, reasonable agreement is found in Fig. 11 between Reynolds stresses, computed as the cross-product of the axial and radial velocity fluctuations, whether the radial velocity component and its fluctuation is directly measured or indirectly estimated from direct axial and inclined component measurements. Moreover, reasonable agreement is found between the present measurements and the data of [14] in Fig. 12.

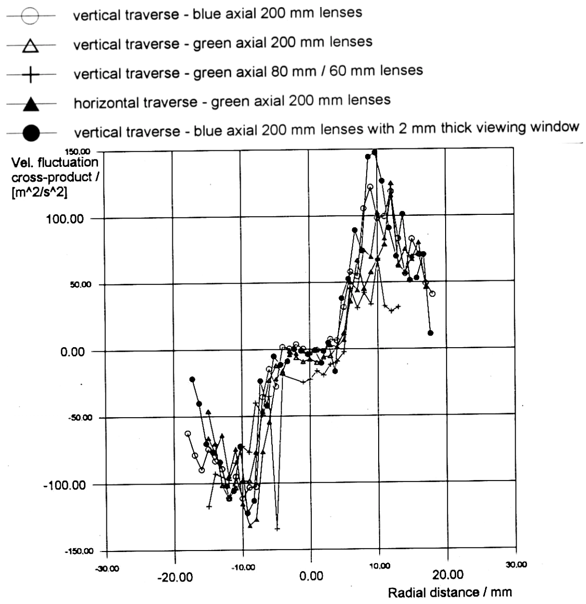


Figure 11: Axial-radial velocity fluctuation cross product (Reynolds stress)

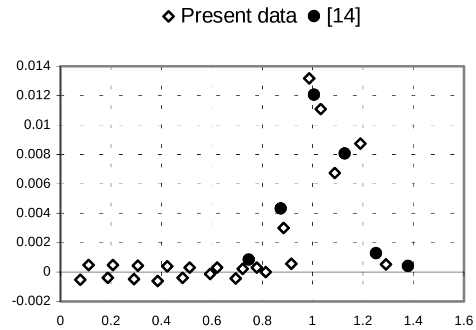


Figure 12: Shear stress profile. Comparison with literature.

5.2 Streamwise development of the jet

The evolution of the measured mean axial velocity along the jet axis is favourably compared to a series of data from the literature [14-16] in Fig. 13. The measured evolution of the axial velocity component fluctuation RMS along the jet axis is compared to data from [14-17] in Fig. 14. It is interesting to note that the original measurements, as affected by the blower-induced noise (determined by high frequency hot wire measurements), compare favourably with the forced jet turbulence data of [15]; the corrected data (after extraction of the blower-induced turbulence) agree reasonably with the unforced data of Fig. 14.

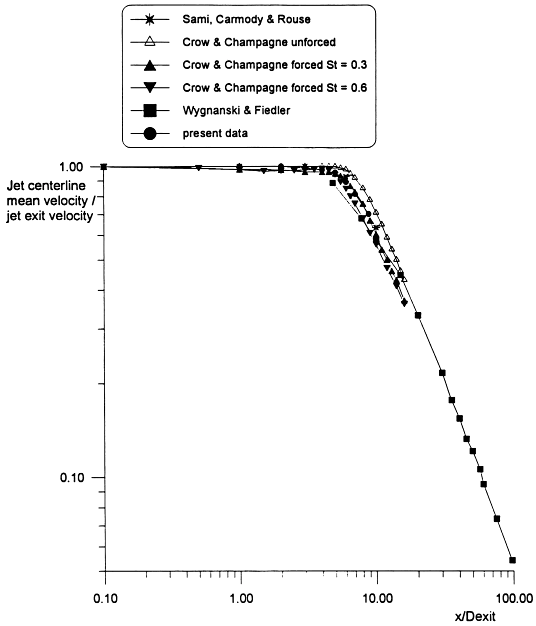


Figure 13: Evolution of centerline velocity along jet axis. Comparison to literature data.

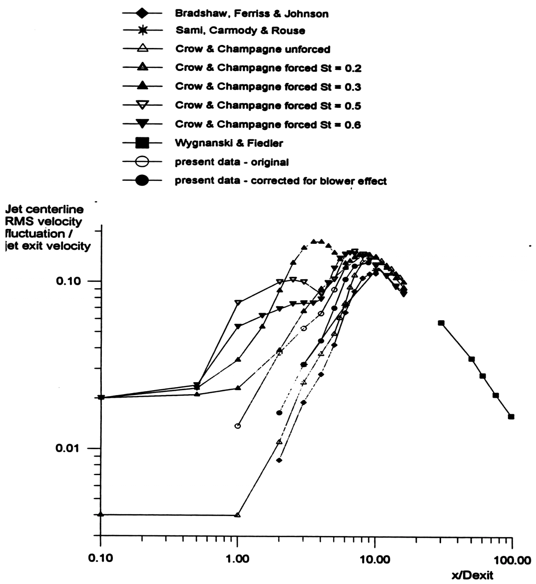


Figure 14: Evolution of RMS velocity fluctuations along jet axis. Comparison to literature data.

Fig. 15 shows the axial evolution of the centerline fluctuations of the three velocity components and their comparison with the data of [14,16]. It is of interest to note the minimum measurable threshold (of about 6%) for the indirectly estimated radial component at the early stages of the jet development and the blower effect as extracted from the measured axial component velocity fluctuations.

Lastly, attention is drawn to the axial development of the Reynolds stresses at the jet circumference (where they exhibit a peak), and their good comparison with the data of [17] in Fig. 16.

6. CONCLUSIONS

The 3D LDA velocity measurement system of LTT/NTUA has been adjusted in terms of hardware and software to optimize its measurement capabilities in typical turbomachinery applications. Particular emphasis was placed on the highly accurate alignment of the three probe volumes and the attainment of spatial and temporal coincidence of the three directly measured velocity components, as this was necessary for the minimization of error amplification through post-processing of the data and the establishment of good quality turbulence quantities.

Unavoidably, the need for spatial and temporal coincidence has led to a significant reduction in attainable data rates to approximately 15% of the individual component data rates offered by the system.

The main residual limitations of the measurement chain include:

- a relatively high minimum measurable turbulence intensity for the indirectly estimated velocity component (due to excessive error amplification through post-processing caused by the necessarily small angle between the two probes in turbomachinery applications)
- a modest bias in mean velocity measurements in regions of high turbulent intensity and low mean velocity, or regions of high velocity gradient
- too low data rates for any meaningful spectral analysis in high speed turbomachinery applications

Overall, the present results substantiate the capability of the system to perform meaningful turbulence field measurements in turbomachines. Post-processing techniques, such as numerical filtering and particle residence time weighting, may further improve the quality of results. Particular attention is necessary in maximizing data rates (through optimization of the seeding and the data acquisition hardware settings), while proper orientation of the three directly measured velocity components (such that they are all three of similar and significant magnitude, for example) may enhance the attained accuracy of results.

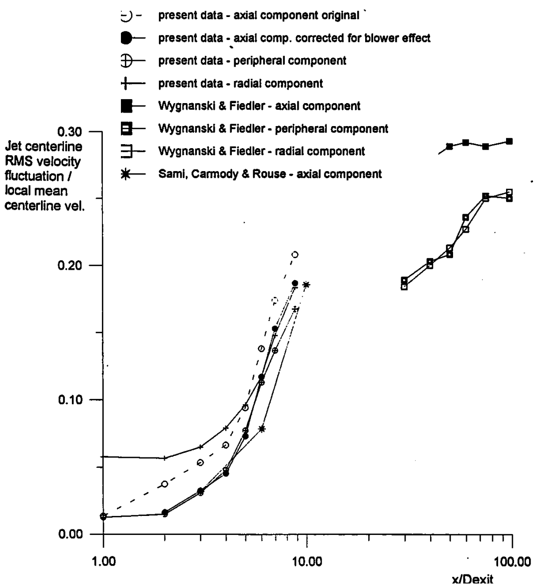


Figure 15: Evolution of RMS velocity fluctuations along jet axis. Comparison with literature.

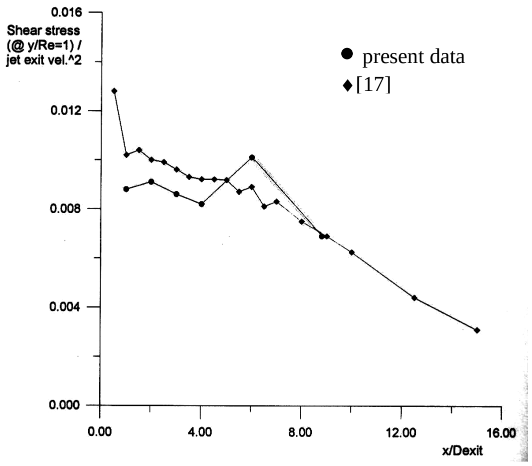


Figure 16: Evolution of normalized shear stress along jet at y/r_{exit}=1. Comparison to literature data

REFERENCES

[1] Jones, D.G., Parker, R.J. & Wiseall, S.S.: Flow measurements in turbomachinery using laser anemometry and holography. 3rd Intl. Conf. on *Laser Anemometry -Advances and Applications*, University College of Swansea, Sept. 1989.

[2] Lepicovsky, J.: Data reduction procedures for laser velocimeter measurements in turbomachinery rotors. 7th Intl. Symp. on *Applications of Laser techniques to Fluid Dynamics*, Lisbon, July 1994.

[3] Brun, K. & Flack, R.D.: A method to measure periodic velocity fields in multielement turbomachines with discrete sampling. Measurement Science and Technology. Vol. 5, 1994, pp. 418-425.

[4] Edmonds, J.D. , Wiseall, S. & Harvey, D.: Recent developments in the application of laser Doppler anemometry to compressor rigs. *Advanced Non-Intrusive Instrumentation for Propulsion Engines, 90th* AGARD-PEP Symposium, Brussels, Oct. 1997.

[5] Doukelis, A., Mathioudakis, K. & Papailiou, K.: Investigation of the 3D flow structure in a high speed annular compressor cascade for tip clearnce effects. Submitted to ASME Turbo-Expo, 1997.

[6] Tropea, C.: Laser Doppler anemometry - recent developments and future challenges. Measurement Science and technology, Vol. 6, 1995, pp. 605-619.

[7] Orloff, K.L. & Snyder, P.K.: Laser Doppler anemometer measurements using non-orthogonal velocity components - error estimates. Applied Optics, Vol. 21,No. 2, Jan.1982.

[8] Carrotte, J.F. & Britchford, K.M.: The effect of laser beam orientation on the accuracy of 3D LDA measurements within an annular test facility. 7th Intl. Symp. on *Applications of Laser techniques to Fluid Dynamics*, Lisbon, July 1994.

[9] Doukelis, A., Mathioudakis, K., Founti, M. & Papailiou, K.: 3D LDA measurements in an annular cascade for studying tip clearance effects. *Advanced Non-Intrusive Instrumentation for Propulsion Engines,* 90th AGARD-PEP Symposium, Brussels, Oct. 1997.

[10] Simeonides, G.: Investigation of high speed turbomachinery flows with laser Doppler anemometry. LTT/NTUA Report, CEU Contract ERBFMB1CT961706, March 1998.

[11] Swales, C., Rickards, J., Brake, C.J. & Barrett, R.V.: Development of a pin-hole meter for aligning 3D laser Doppler anemometers. *Laser Anemometry,* Dantec Information, No. 12, Feb. 1993.

[12] Kuhlman, J.M. & Gross, R.W.: Three-component velocity measurements in an axisymmetricjet using LDV. *Laser Anemometry,* Dantec Information, No. 12, Feb. 1993.

[13] Hussein, H.J., George, W.K. & Capp. S.P.: Comparison between hot wire and burst-mode LDA velocity measurements in a fully developed turbulent jet. AIAA Paper 88-0424, Jan. 1988.

[14] Sami, S., Carmody, T. & Rouse, H.: Jet diffusion in the region of flow establishment. *J. Fluid Mechanics*, Vol. 27, Part 2, 1967, pp.231-252.

[15] Crow, S.C. & Champagne, F.H.: Orderly structure in jet turbulence. *J. Fluid Mechanics*, Vol. 48, Part 3, 1971, pp. 547-591.

[16] Wygnanski, I. & Fiedler, H.: Some measurements in the self-preserving jet. *J. Fluid Mechanics*, Vol. 38, Part 3, 1969, pp. 577-612.

[17] Bradshaw, P., Ferriss, D.H. & Johnson, R.F.: Turbulence in the noise-producing region of a circular jet. *J. Fluid Mechanics*, Vol. 19, 1963, pp. 591-624.

ACKNOWLEDGEMENT

The participation of the first author to this work was supported by a TMR Return Grant Contract from the Commission of the E.U.