Multicolor Fiberoptic Laser-Two-Focus Velocimeter for Three-Dimensional Flow Analysis

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The paper first gives an overview of the state of the art of Laser-Two-Focus (L2F) velocimetry. New developments of laser velocimetry related to turbomachinery applications are also discussed. The main part of the paper describes two new L2F concepts based on optical fibers for two-dimensional and three-dimensional velocity component measurements. A multicolor two-dimensional system with selectable beam separation is presented that enables a considerable measuring time reduction, particularly in flows of high turbulence intensities. A new three-dimensional L2F method is introduced that is based on an axial displacement between start and stop beam centers. The effects of main geometrical parameters on the system's sensitivity have been studied theoretically, using two methods of modeling the measuring procedure. The theoretical results are discussed and compared with recent experimental data.

Nomenclature

A	= system with positive axial beam center displacement
a	= radius coordinate of laser beams
B	= system with negative axial beam center
B	= displacement index indicating blue
C_1, C_2	= integral boundaries
d	= diameter of the laser beams in the probe volume
G	= index indicating green
I, I_0	= intensity of light
I	= integral value of successful dual beam transits
L	= axial length of the L2F probe volume
P, P_α, P_t	= integrated probability density functions
P	= probability density function
P_I	= probability according to probe volume intensity distribution
P_{succ}	= probability of a successful two-beam transit
s, s'	= separation of the beams in the L2F probe volume
Tu_i	= turbulence intensities
u_1, u_2, u_3	= Cartesian components of the velocity vector u
ΔZ	= axial displacement of measurement volume centers
α	= circumferential angle coordinate
α, α_0	= angle setting of the L2F beams plane
β	= angle of flow vector with the plane normal to the optical axis
γ	= angle of volume centers with the plane normal to the optical axis
ε_S	= measuring error biasing mean velocity
ε_T	= measuring error biasing turbulence intensities
ρ	= correlation coefficient
$\sigma_i, \sigma_\alpha, \sigma_d$	= standard deviations

Subscripts

$\parallel$	= parallel polarization
$\perp$	= perpendicular polarization

Introduction

LASER-TWO-FOCUS (L2F) velocimetry has achieved importance in experimental fluid flow analysis comparable to LD velocimetry. Several L2F systems are commercially available, and some industrial and research organizations have built their own systems for inhouse use. A variety of designs exist that are suited to many different uses. These include applications for long-range wind speed measurements and for measurements in heat exchangers, wet steam flows, water pumps, plasma flows, diesel engines, and wind and cascade wind tunnels.

The most common application of the L2F technique is in the experimental investigation of turbomachinery flow. Numerous reports have been published that present results of measurements in centrifugal and axial compressors as well as turbines. A survey of L2F literature is given by Schodl.[1]

Detailed laser velocimetry data have contributed a great deal to our improved understanding of turbomachinery internal flow. This is especially true for rotor flows, which are generally inaccessible to conventional measuring techniques. Comparisons between laser data and theoretical predictions have resulted in improved mathematical models and design procedures.

One of the salient properties of the L2F technique is its significant signal-to-noise ratio. This plays an important role when examining the flow in narrow blade channels and in boundary layers. However, boundary-layer flows are characterized by high turbulence intensities. Under such conditions, the L2F measuring process becomes rather time consuming. For higher turbulence intensities, the probability of a successful dual beam transit reduces and measuring time increases.

Continued development of the L2F technique has attempted to overcome this shortcoming. A system was proposed by Tanner[2] and constructed by ONERA[3] that replaces the two round spots in the L2F probe volume by two dashes. This system operates like a two fringe laser doppler anemometer. At a certain orientation of this two-dashes probe volume, the velocity component parallel to the fringe normal can be measured. Particle crossings are much more likely because the effective area of the dashes is much larger than that of the small cylinders of a usual L2F system. This significantly reduces the measuring time.

A similar system with two double dashes was recently developed at NASA Lewis Research Center.[4] This system incorporates the exciting idea of Lading[5] by which quasitime-filtered signals can be obtained. This should enable a better pulse-center determination and reduced signal noise.

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The advantage of both systems is a reduced measuring time. However, due to beam magnification in the probe volume, the signal-to-noise ratio is simultaneously reduced. At DLR another solution for reducing the measuring time was found that preserves the inherent high signal quality of the two-focus system. This system is described in the first part of the paper.

Great emphasis has been placed upon the development of three-dimensional velocimeters for turbomachinery application. The typical arrangement of three-dimensional velocimeters—two two-dimensional velocimeters separated by an angle of about 30 deg—usually cannot be applied to turbomachinery applications because only small windows can be installed in curved turbomachinery casings. Systems are therefore required that need only one common collimator lens for transmitting the laser beams and receiving the scattered light. A three-dimensional laser doppler anemometry (LDA) system that features a single collimator lens was used by Seasholtz and Goldman.[6] This system combines a fringe-type LDA and a scanning Fabri-Perot interferometer. The transverse velocity components are measured by the fringe system; the on-axis component is measured by analyzing the frequency of the scattered light directly.

A L2F system for three-component velocity measurements was introduced and demonstrated in 1981 at DLR. The system, which consists basically of two two-dimensional L2F systems of different color, was described in detail by Schodl.[1] This three-dimensional velocimeter is still under development. A final version is expected in 1989.

A new three-dimensional method based on the L2F system has been found that incorporates fiber optics. The measurement principle and hardware used in this new method are described in the second part of the paper.

Two-Dimensional Multicolor L2F System

The application of L2F velocimetry is limited to flows with turbulence levels less than 30%. At high turbulence intensity, there are significant occurrences of zero or negative velocities, which cannot be measured. This leads to an incomplete histogram, and calculation of mean values will be erroneous. A more practical limitation is that the measuring time increases with increasing turbulence intensity and becomes remarkably long at turbulence intensities exceeding 25%.

The relation between measuring time, flow turbulence, and probe volume geometry has been considered by several authors (e.g., Brown[7] and Hayami et al.[8]); however, the Gaussian intensity distribution of the laser beams in the probe volume was never taken into account.

The ratio of beam diameter to beam separation in the L2F probe volume determines an angle interval within which particles will intercept both laser beams and contribute to the time of flight histogram. The probability for successful interception of both beams is not equally distributed within this angle range. The Gaussian intensity distribution causes the signals of particles passing through the centers of the beams to have a much higher amplitude than those of particles passing the peripheral section of the beams (see Fig. 1). The intensity distribution described by

$$\frac{I}{I_0} = \frac{4}{\sqrt{2\pi}\, d} \exp\left(-\frac{a^2}{2(d/4)^2}\right) \tag{1}$$

is a measure of the probability of successful crossings. With the assumption

$$\alpha - \alpha_0 = \arc\tan\frac{2a}{s} \cong \frac{2a}{s} \tag{2}$$

and the fact that for flow direction $\alpha = \alpha_0$ the probability must be 1, we can write

$$\frac{I}{I_0} \sim P_I = \exp\left(-\frac{(\alpha-\alpha_0)^2}{2\sigma_d^2}\right) \tag{3}$$

with

$$\sigma_d = \frac{d}{2s} \tag{4}$$

The probability density function $P_\alpha(\alpha)$ describes the probability that a turbulent flow has a certain flow direction. This distribution has a Gaussian shape that agrees with measurements. The normalized relation is

$$P_\alpha(\alpha) = \frac{1}{\sqrt{2\pi}} \cdot \frac{1}{\sigma_\alpha} \exp\left(-\frac{(\alpha-\alpha_0)^2}{2\sigma_\alpha^2}\right) \tag{5}$$

with

$$\sigma_\alpha \cong \arc\tan\frac{\sqrt{\overline{u_2'^2}}}{u_\perp} \cong \arc\tan Tu_2 \cong Tu \tag{6}$$

assuming isotropic turbulence.

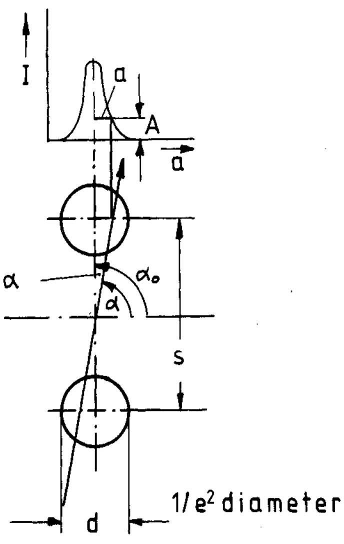

Fig. 1 Intensity distribution within the L2F probe volume.

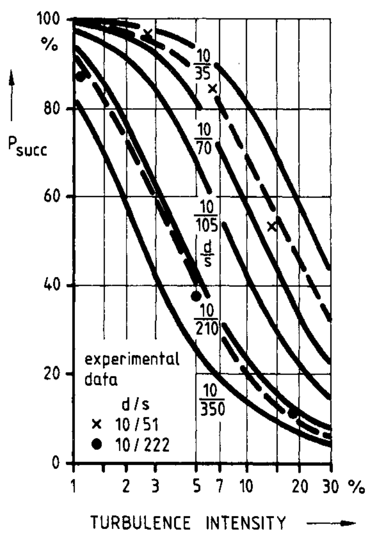

Fig. 2 Probability of successfully crossing both beams.

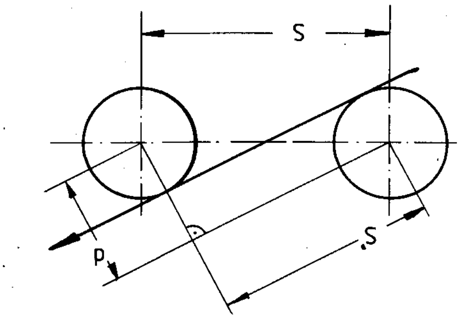

Fig. 3 L2F probe volume geometry (error of beam separation).

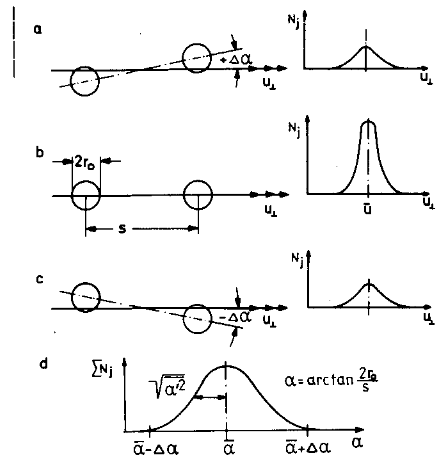

Fig. 4 L2F probe volume (error of angular turbulence).

Assuming that the plane containing the laser beams is oriented in the direction $\alpha = \alpha_0$, the probability of successful time of flight measurements is given by

$$P_{\text{succ}} = \int_{-\infty}^{+\infty} P_\alpha(\alpha) \cdot P_I \, d\alpha$$

$$= \int_{-\infty}^{+\infty} \frac{1}{\sqrt{2\pi}} \frac{1}{\sigma_\alpha} \exp\left(- \frac{(\alpha - \alpha_0)^2 (\sigma_d^2 + \sigma_\alpha^2)}{2 \cdot \sigma_\alpha^2 \cdot \sigma_d^2} \right) d\alpha$$

$$P_{\text{succ}} = \frac{\sigma_d}{\sqrt{\sigma_d^2 + \sigma_\alpha^2}} = \left[1 + \left(\frac{2s}{d} \, Tu \right)^2 \right]^{-\frac{1}{2}} \tag{7}$$

The results are shown in Fig. 2. The typical L2F probe volume has a beam diameter to beam separation ratio of about $d/s = 10/350$. In this case, the probability of successful interception of both beams drops to 13% at 10% turbulence intensity. When increasing the d/s ratio, this value can be considerably improved.

Simultaneously, a systematic error that is controlled by the beam spacing increases, as illustrated in Fig. 3. A particle passing through the beam centers travels a distance s. However, a particle that just touches the edge of each beam as shown in Fig. 3 travels a distance s'. These two distances are related by

$$s' = s \cdot \cos \arcsin \frac{d}{s} \tag{8}$$

Substituting the beam dimensions, the error ε_s was calculated:

$$\varepsilon_s = \frac{s - s'}{s} = 1 - \cos \arcsin \frac{d}{s} \tag{9}$$

For an error $<1\%$, the d/s ratio must be smaller than 0.14 (10/70).

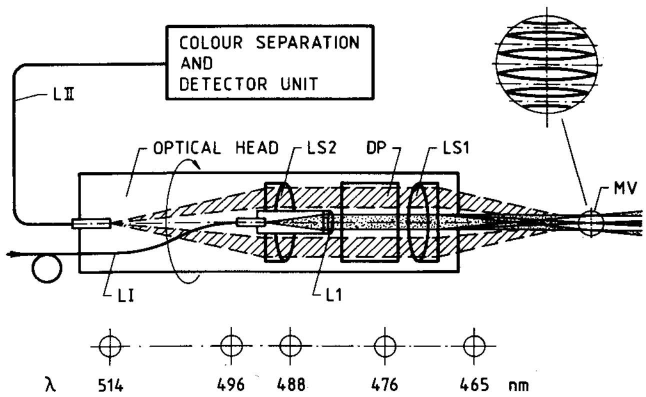

Fig. 5 Optical beam path of the multicolor fiber-optic L2F velocimeter.

A second limiting factor for the d/s ratio is the lowest measurable turbulence intensity, as illustrated by Fig. 4. If a laminar flow with no flow angle fluctuations is assumed, the orientation of the beams' plane can be selected within a certain angle range that depends on the d/s ratio and measurements then can be taken. A P_α distribution with a certain standard deviation, $\sigma_d = d/2s$, results, indicating a turbulence that in fact does not exist in the flow.

If Eq. (5) describes the real P_α distribution that exists in a turbulent flow, then the distribution measured with a L2F system is

$$P_{\alpha_i \text{ meas}} \sim \int_{-\infty}^{+\infty} \frac{1}{\sqrt{2\pi}} \frac{1}{\sigma_\alpha} \exp\left(- \frac{(\alpha - \alpha_0)^2}{2\sigma_\alpha^2} \right) \exp\left(- \frac{(\alpha - \alpha_i)^2}{2\sigma_d^2} \right) d\alpha \tag{10}$$

with α_i the varying angle setting of the plane containing the beam pair. The variance $\sigma_{\alpha \text{ meas}}$ of this new $P_{\alpha_i \text{ meas}}$ distribution is

$$\sigma_{\alpha \text{ meas}} = \sqrt{\sigma_\alpha^2 + \sigma_d^2} \tag{11}$$

From Eqs. (4) and (6) it follows that

$$Tu_{\text{meas}} = \sqrt{Tu^2 + \left(\frac{d}{2s} \right)^2} \tag{12}$$

Equation (12) can be used to reduce the measured turbulence intensities to get the true values when the geometrical properties of the probe volume are known. This can be done with sufficient confidence provided

$$\sigma_d \leq Tu \tag{13}$$

or

$$\frac{d}{s} \leq 2Tu \tag{14}$$

The conclusion is that a minimum measuring time can be realized without losing measurement accuracy if the probe volume dimensions are matched to the flow turbulence intensities. Small values of the beam diameter-to-separation ratio are required in flows of low turbulence intensities, and high values can be tolerated for higher turbulence intensities.

The beam diameter should be small and constant, about 10 μm, since the beam diameter determines the signal-to-noise ratio. Therefore, it is desirable to vary the beam separation only. This can be realized either by the application of exchangeable optical elements or by a special optical design. Because of the difficulty in continuously varying beam separation while maintaining the system alignment, stepwise selectable beam separations were chosen.

The optical setup of a new multicolor, fiber-based L2F system that implements selectable beam separations is shown in Fig. 5.

In this design, the light from an argon-ion-laser operated in multicolor mode is coupled into a single-mode fiber, LI, and guided to the optical head. The divergent laser light emitted from the fiber end is collected by the lens L1. The parallel laser beam passes a special color dispersing prism, DP, which separates the different colors. They are focused in the measurement volume by lens LS1 and yield a set of parallel beams of different colors and different distances as shown in the details.

Backscattered light from particles passing through the beams of different colors is collected by the outer part of the collimator lens, LS1, recombined by the dispersing prism, DP, and focused by lens LS2 into a single multimode fiber, LII. This fiber carries the multicolor light to a color separation and detector unit, as shown in detail in Fig. 6. The different colors of the detected light were directed separately into a set of fibers and guided to a switching unit, SE, by an arrangement of two lenses, L5 and L6, and a dispersing prism, DP2. With this device, two arbitrarily selectable colors can be switched to the start and the stop photomultiplier tubes, thus selecting different beams in the probe volume. The chosen color combination corresponds to a distinct beam separation that is roughly proportional to the wavelength difference (see lower part of Fig. 5).

The optical elements of this multicolor fiber system are mounted into the hollow shaft of a stepper motor, which is used to rotate the whole system for adjusting the beam's plane to the flow direction. The result is a small device that is the basis of a system with the beam expander shown in Fig. 7. The working distance is 350 or 500 mm. The rotating basis unit is mounted on the left side. Specially designed achromatic optics are required to avoid an axial displacement of the different colored beams in the probe volume. The data processing electronics have not required any changes.

Some tests within a turbulent free jet have been carried out. The measurement positions were varied along the jet axis to provide measurements in flow regions of different turbulence intensities. Two beam separations with a d/s ratio of 10/51 and 10/222 were chosen. The probability of successful dual beam transits was determined by the ratio of successful measurements referred to start counts. The beam's plane was orientated parallel to the mean flow direction. These data are plotted in Fig. 2. The dashed curve indicates the theoretical data predicted for the experimental d/s ratios. The good agreement of data proves the predicted measuring time reduction.

Three-Dimensional Multicolor L2F System

By changing a few optical elements, the described fiber-optic device can be transformed into a system that enables three-dimensional velocity measurements.

The dashed regions within beams S1 and S2 of the L2F probe volume shown in Fig. 8 indicate the axial length where particles can be detected. The highest sensitivity is in the beam centers, F1 and F2. If the particle flow penetrates the two beams perpendicular to the axis ($\beta = 0$), the effective length of the probe volume is L. The number of successful dual beam transits is related to the integral value I of the probability distribution of the time-of-flight measurements.

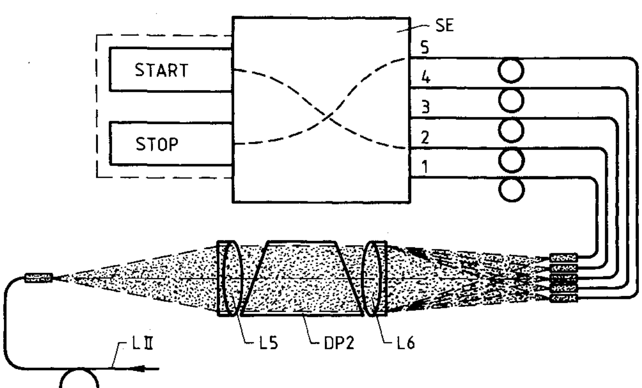

Fig. 6 Color-separation and detector unit.

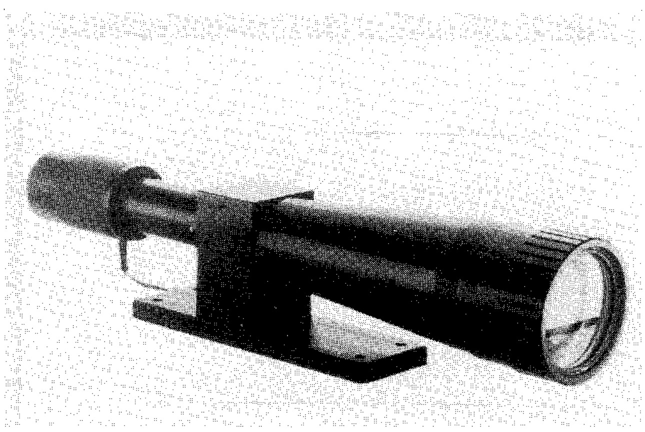

Fig. 7 Multicolor fiber-based L2F system with beam expander.

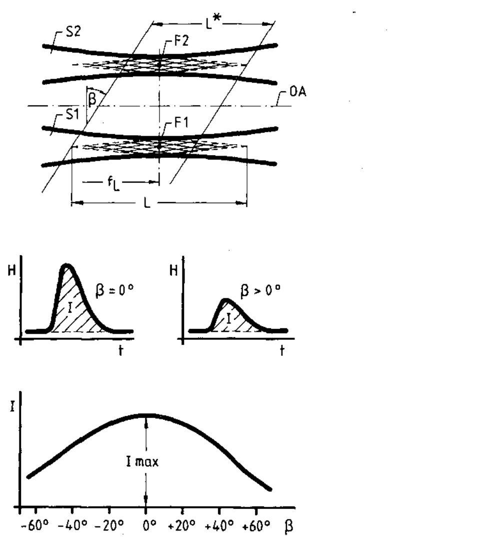

Fig. 8 Dependence of measuring rate on the elevation angle of flow vector.

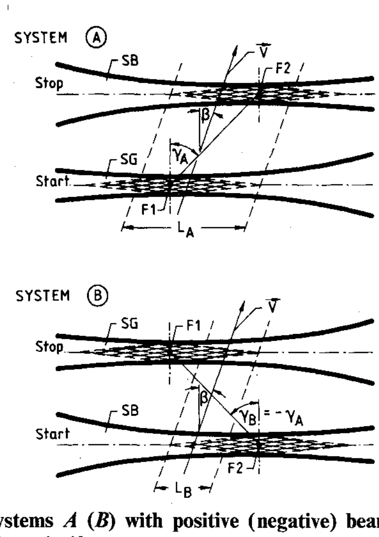

Fig. 9 Systems A (B) with positive (negative) beam center displacement [angle γ_A (γ_B)].

If the flow vector has an on-axis component ($\beta > 0$), the actual length of the probe volume is reduced to L_*, thus lowering the measuring frequency, indicated by a smaller integral value I. The function I over β, shown at the bottom of Fig. 8, is used to measure the on-axis component.

In Fig. 9 two systems are shown with an axial displacement between the stop and the start beam centers. This displacement is determined by the angle γ_A. The system A with a positive displacement will be most sensitive if the flow direction is parallel to the connecting line of the beam centers ($\beta = \gamma_A$) indicated by a maximum of the measuring frequency.

The system B with an opposite displacement will indicate the maximum measuring frequency if the flow angle β is γ_B. As the example of an arbitrarily chosen flow vector shows, positive axial flow components lead to a higher measuring frequency with system A compared to system B. This is indicated by the different actual probe volume lengths L_A and L_B that are determined by the opposite edges of the probe volumes and the flow angle β.

In Fig. 10, the measuring rate is shown as a function of the flow angle for both systems.

The ratio of the measurement frequencies of both systems, $(I_A - I_B)/(I_A + I_B)$, is a sensitive measure of the axial velocity component, provided $|\beta|$ does not exceed $\gamma_{A,B}$.

A B-type system will result by rotating system A (see Fig. 9) by 180 deg and exchanging start and stop channels. Both systems read the same mean values of flow angle, magnitude, and turbulence intensities of the velocity component perpendicular to the beam axis. Only the measuring frequency is different, and this is the measure of the on-axis component.

The measuring frequency ratio of system A against B has to be calibrated as a function of the flow angle β.

The two-dimensional multicolor L2F setup shown in Fig. 5 can be transformed very easily into a three-dimensional system if the achromatic collimator lens, LS1, of the setup is replaced by a lens that introduces slight chromatic aberrations. This results in different focal points for the different colors. The axial displacement of the beam centers depends on the lens design and on the wavelength difference of the selected start- and stop-laser beams.

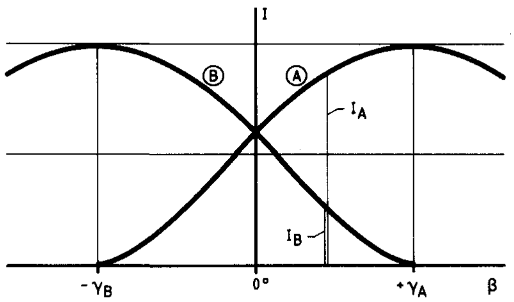

Fig. 10 Dependence of measuring rate of system A (B) on the flow angle β.

Using this system, two sets of measurements are required to get the three-dimensional velocity information. The second set of measurements is made after rotating the plane of the laser beams by 180 deg relative to the beam plane orientation used for the first set of measurements. To save time, a system allowing simultaneous measurements was developed that is similar to the system with the variable beam separation (see Fig. 11).

The color-splitting prism is replaced by a Wollaston prism, PP1, that produces two slightly diverging beams of orthogonal linear polarization. This will be also true if a multicolor argon laser beam is used. From the inner part of the collimator lens, two parallel, multicolor beams of different polarization are imaged into the probe volume. However, due to chromatic aberration of the selected lens, LS1, each of the different colors is focused with a slight displacement along the optical axis. In the enlargement, the three-dimensional L2F probe volume is shown for the two most powerful colors (green and blue). The light scattered from particles passing through these four beam foci is gathered by the same lens, LS1, and returned through the polarizing prism, PP1. A second Wollaston prism, PP2, and a lens, LS2, are used to separate the different polarized parts of the scattered light for coupling into two multimode fibers.

After color separation (see Fig. 6) in two separate units, four detectors are adjusted to the four beam regions in the probe volume. Thus, two integrated L2F systems are formed. System A measures the time of flight between $B_{\|}$ and $G_{\perp}$ and system B between $G_{\perp}$ and $B_{\|}$. The data acquisition of both systems is carried out simultaneously by the application of two sets of electronics. The design of the optical head is identical to the two-dimensional multicolor shown in Fig. 7, since the systems differ by only a few optical parts.

Theoretical simulations were carried out to predict the influence of various flow and geometrical parameters on the calibration and sensitivity of the three-dimensional L2F. At first a L2F simulation routine[9] was extended to include axial displacement of the beam centers in the measuring volume. The start and stop foci were modeled as cylinders with adjustable diameter, length, and spacing. With a three-dimensional random number generator, a great amount of model particles was formed within the start focus. The flight path of each particle was checked to determine whether or not it hit the stop focus. The percentage of "scored" particles is a measure of the expectation of hitting the stop focus. The intensity distribution, which influences the visibility of the particles, was modeled by a higher particle concentration within the center part of the start cylinder than within the peripheral region. The sensitivity of the three-dimensional L2F is defined as the difference related to the total number of scored hits for the two crossed L2F systems, $(I_A - I_B)/(I_A + I_B)$.

Figure 12a shows the sensitivity as a function of the mean flow angle β with respect to the beam perpendicular plane.

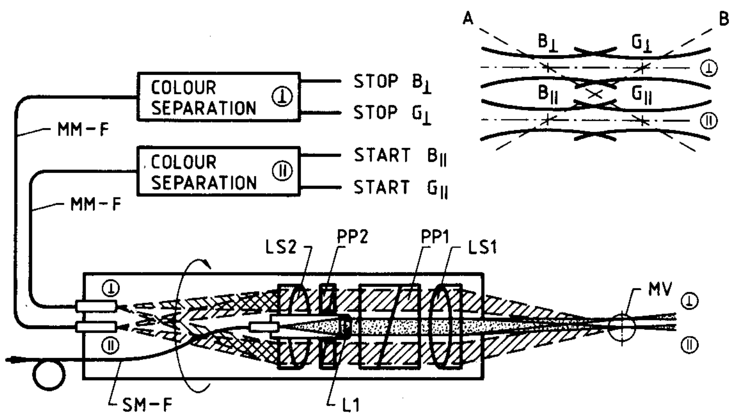

Fig. 11 Beam path of the three-dimensional multicolor L2F velocimeter.

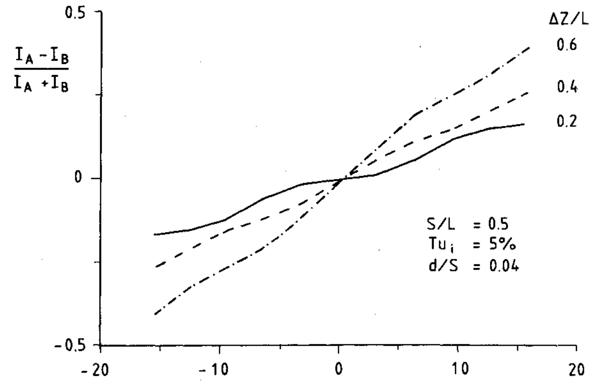

Fig. 12a Predicted sensitivity of three-dimensional L2F.

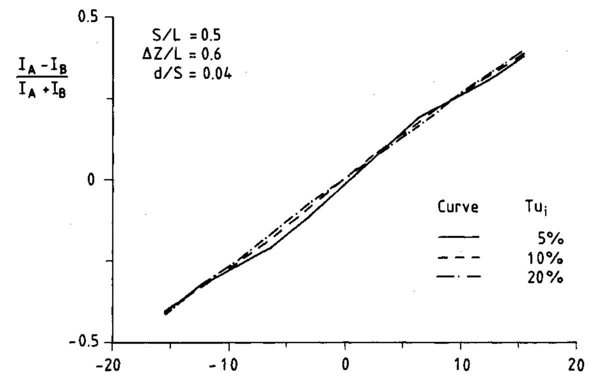

Fig. 12b Influence of turbulence level on predicted sensitivity.

The results were calculated for three different axial displacements of the measurement volumes: $\Delta Z/L = 0.2$, 0.4, and 0.6. Focus spacing to measurement volume length was $s/L = 0.5$, beam diameter to focus spacing was $d/s = 0.04$, and the turbulence level was 5%. The orientation of the focus pair was varied with respect to the mean flow angle α, as in a real L2F measurement. For these simulations, 28 different angle settings with an angle step size of 2.2 deg were used. In each angle setting, 4800 model particles were evaluated. The results in Fig. 12a clearly show the increasing sensitivity of the three-dimensional L2F when the axial displacement of the measurement volumes is increased. In Fig. 12b, the sensitivity was calculated for a constant axial displacement of $\Delta Z/L = 0.6$, but for 5 different (isotropic) turbulence levels. The data reveal no obvious effect of flow turbulence on the sensitivity of the three-dimensional L2F. However, since this is a result for one special geometry, no general conclusion can be drawn yet. The scatter in the data, which seems to indicate a slightly nonuniform behavior, was probably caused by the limited number of particles. Due to computer time limitations, greater particle numbers were not tested.

To avoid the time-consuming calculation of many random numbers, an additional faster method for L2F simulation was developed. In the model, the flow is considered to be a three-dimensional (Gaussian) normally distributed random function with three mean flow vector components, u_1, u_2, u_3, and three turbulence levels, Tu_1, Tu_2, Tu_3. Additionally, anisotropic turbulence may be described by three correlation coefficients, ρ_1, ρ_2, ρ_3. To simplify the explanation, the one-dimensional simulation procedure is described. For a flow that has turbulent fluctuations only in the direction of the laser beam axis, the probability density function is (see Fig. 13)

$$P(u_3) = \frac{1}{\sigma_3\sqrt{2\pi}} \cdot \exp\left(-\frac{(u_3 - \bar{u}_3)^2}{2\sigma_3^2}\right) \tag{15}$$

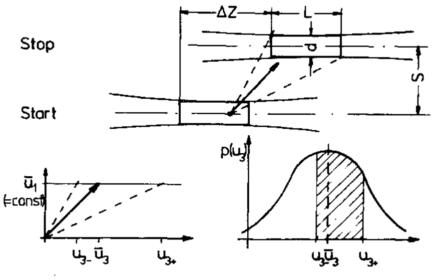

Fig. 13 One-dimensional model for turbulent fluctuations.

Particles that pass arbitrary locations within the start focus are assumed to have a flow characteristic following this probability distribution. As seen in Fig. 13, only those particles that have a u_3 component larger than u_{3-} and less than u_{3+} will hit the stop focus. The probability of successfully hitting the stop focus is

$$I = \frac{1}{\sqrt{\pi}} \int_{C_1}^{C_2} \exp(-u_3^2)\, du_3 \tag{16}$$

that can be expressed by the error function; C_1 and C_2 are functions of the measurement volume geometry, the origin of the particle within the start focus and the flow parameters (e.g., turbulence level). By direct integration of the probability density function, the probability of hitting can be calculated quickly and conveniently. The extension to a three-dimensional probability distribution is possible without difficulties. Based on the described method, a simulation program was coded. Various assumptions were made during the calculations:

1) Flow turbulence is described by a three-dimensional Gaussian normal distribution.
2) Particles start from arbitrary locations of the start focus centerline.
3) Measurement volumes have constant intensity.
4) Particle size is constant.
5) No noise exists (i.e., no apparent events caused by different particles or hardware imperfection).
6) Focus pair is aligned to mean circumferential flow angle.

Some results of the computations are shown in Figs. 14a–14c. In all figures, the sensitivity of the three-dimensional L2F-model is shown as a function of turbulence level. The flow angle β (between mean flow direction and the beam perpendicular plane) is used as a parameter with a step size of 4 deg. Due to symmetry, only data for positive angles were calculated. The other parameters preset for the data in Fig. 14a were isotropic turbulence ($\rho_1 = \rho_2 = \rho_3 = 0$, $Tu_1 = Tu_2 = Tu_3$), $s/L = 0.65$, $d/s = 0.04$, and $\Delta Z/L = 0.65$.

For each angle β, the solid line shows the results for the whole three-dimensional computation, and the dashed line is a comparison of the one-dimensional calculation (only fluctuations in beam direction). Figure 14b shows computational results with the parameters of Fig. 14a but anisotropic turbulence ($\rho_1 = \rho_2 = \rho_3 = 0.4$, $Tu_1 = Tu_2 = Tu_3$). In Fig. 14c, the geometry of the measuring volume was changed to $s/L = 1.0$ and $\Delta Z/L = 0.5$.

These results indicate that the sensitivity of the three-dimensional L2F depends on the measurement volume geometry. The geometry can be optimized to get a sensitivity that is nearly independent of turbulence level.

Another result of the computations is that the sensitivity can be estimated quite well by the one-dimensional model, which only includes beam spacing/length ratio and axial displacement as geometry parameters. In other applications, the simple model does not suffice, and the fluctuations perpendicular to the beam axis and the focus diameter/beam spacing ratio must be considered. This includes determining the probability of hitting the stop focus if the mean circumferential

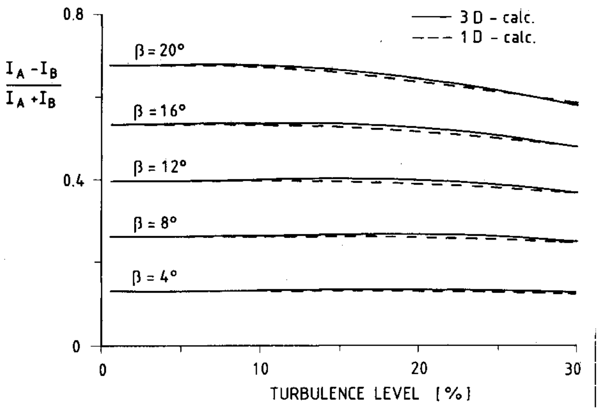

Fig. 14a Three-dimensional L2F sensitivity, $\Delta Z/L = s/L = 0.65$, $\rho_i = 0.0$.

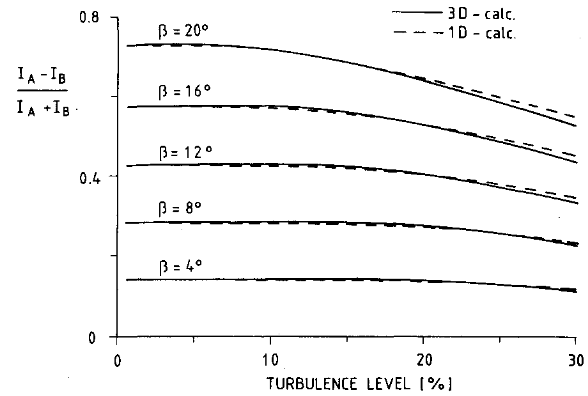

Fig. 14c Three-dimensional L2F sensitivity, $\Delta Z/L = 0.5$, $s/L = 1.0$, $\rho_i = 0.0$.

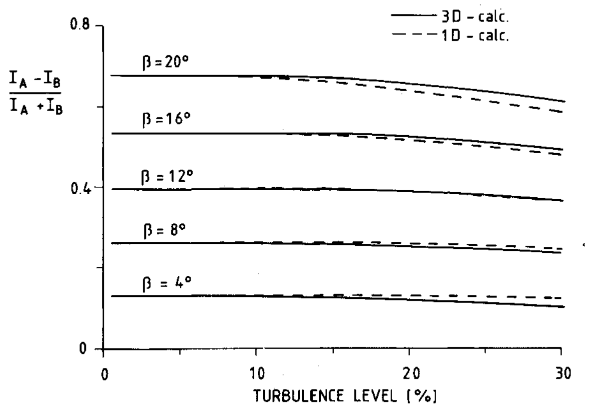

Fig. 14b Three-dimensional L2F sensitivity, $\Delta Z/L = s/L = 0.65$, $\rho_i = 0.4$.

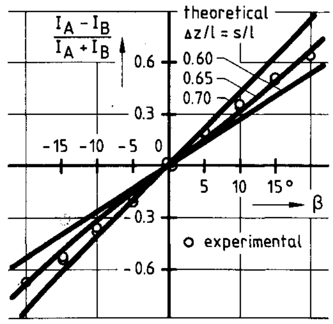

Fig. 15 Experimental and theoretical sensitivity of the three-dimensional L2F system.

flow angle is not aligned with the orientation of the focus pair. Future extensions of the simulation program will include the light intensity distribution within the measurement volume and the effect of different particle sizes. The influence of signal-to-noise ratio on the L2F measurements also will be evaluated.

Some preliminary experiments have been carried out with the three-dimensional L2F system on a small free jet. The three-dimensional optical setup was used with a beam expander (see Fig. 7), and the working distance was 350 mm.

The two most powerful colors of the Ar-laser were selected by appropriately switching the color separator units. The beam diameter d was about 8 μm, the axial center displacement ΔZ of the blue and green beams was 0.2 mm, and the separation s of the different polarized beams was 0.2 mm. The axial length L of each of the four beams was difficult to measure but assessed between 0.25 and 0.4 mm. A more precise measuring technique is still under development. The sensitivity and the reproducibility of the system are proven by the experimental results shown in Fig. 15. A free jet was used for the calibration tests. From the orientation of the nozzle axis, the flow angle β was determined. The measurement point was on the nozzle axis just one nozzle diameter downstream of the nozzle outlet. The flow turbulence was about 1.5%.

Theoretical calculations were made for comparison with the experimental data. The parameters $\Delta Z/L$ and s/L were set equal and varied between 0.6 and 0.7 to obtain a theoretical estimate for the real probe volume length. The flow at the nozzle exit was considered to have isotropic turbulence ($\rho_i = 0$). Best agreement was achieved with a relative focus displacement of $\Delta Z/L = 0.65$. This corresponds to a probe volume length of 0.325 mm, which is well within the estimated range.

This calibration curve demonstrates the high sensitivity of this three-dimensional L2F method. The low scatter of the sampled data indicates that an angle resolution of about 1 deg is expected.

Conclusion

Two new L2F concepts are described. Both concepts feature multibeam, multicolor optical arrangements. The advantage of the first system is its potential for saving measuring time. With the multibeams concept, the beam separation can be matched to the flow turbulence intensity. Thus, a measuring time reduction by a factor of 5 is achieved without losing measuring accuracy. The system design is based on optical fibers. All optical elements fit into a small, rotatable optical head that is connected with the laser and the photomultipliers via fibers.

The second new system described here enables measurement of all three velocity components with a small viewing angle. The measuring time of this three-dimensional L2F system is comparable to conventional two-dimensional systems. The results of preliminary model calculations reveal useful information on the proper design of the probe volume geometry. Initial experimental results with a prototype have demonstrated good agreement with the theoretical predictions and have proven the high sensitivity of the method.

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