METHODS OF EXPERIMENTAL INVESTIGATION AND MEASUREMENTS

Laser Tomography for Flow Structure Analysis

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Abstract—A laser tomography system is described that is intended for three-dimensional visualization and analysis of the processes occurring in hydromechanical and gasdynamic flows. Optical schemes are given of three-dimensional illumination of the region being investigated, based on the sweeping light sheet technique. The developed system of optical tomography is used to scan the flow structure being investigated by means of successive optical planes, and the resultant digital images are processed and reconstructed using computer techniques which make it possible to display three-dimensional images of the “frozen” surface structure of flow in different directions. Commercially available standard software packages are used for image and data processing. Results are given of the experimental investigation of a free jet flow by means of optical tomography.

1. INTRODUCTION

At present, two groups of methods are used to investigate the flow structure, namely, point (local) methods such as laser Doppler anemometry (LDA) [1, 2] and integral methods in which the information is obtained simultaneously about the entire velocity field of flows being investigated. The latter methods include, for example, the PIV (Particle Image Velocimetry) and PTA (Particle Tracking Anemometry) [2–7]. While the point methods usually produce time-averaged information, the measurements by the integral methods yield instantaneous information about the flow parameters. Usually, the flow being investigated is illuminated by a plane narrow light beam (light sheet of flow). The particles in this light sheet scatter the incident light, which is photo- or video-recorded and whose analysis enables one to obtain instantaneous information about the parameters of the flow being investigated.

If we assume that a plane light (laser) beam [8] moves through the flow being investigated, and the successive “light sheets” are analyzed using video equipment, we can obtain three-dimensional information about the flow structure. In this case, we refer to laser tomography of flows [7, 9]. The concept of laser tomography of flows is close to the concept of computer tomography widely known in medicine. Tomography is a method of three-dimensional visualization of real structures (objects), which employs conventional video equipment for receiving and processing two-dimensional images and performs subsequent computer-aided reconstruction of three-dimensional structure of flows.

Currently, tomography finds ever expanding application in various fields of science and technology and, first of all, in medicine where X-ray tomography has an important place in the diagnostics and prognostication of various diseases. At the same time, tomography is not associated with the use of a single particular radiation source. From the standpoint of tomography, it is immaterial whether the radiation applied is optical, ultrasonic, or X-ray. It is only the technique of receiving and processing the images that varies. The realization of different forms of sheets of investigated structures (it is presently known to use parallel, spiral, and normal sheets) is not associated with changes in the instrumentation involved.

At present, when optical tomography is used to analyze the flow structure, one can only expect to obtain a qualitative three-dimensional flow pattern reconstructed as a result of computer processing of digital images.

As compared with its applications in other fields of technology and medicine, the application of tomography to problems in fluid mechanics is primarily characterized by the fact that the “object” of investigation in this case is time-dependent rather than static. For example, in medicine the rate of variation of the “object” is low compared with the rate of generation of digital images; therefore, the time resolution of the equipment is of minor importance in the process of medical tomography. In this respect, the application of tomographic methods to problems in experimental flow mechanics presents considerable difficulties, because it is necessary to reconcile the dynamics of the processes being investigated and the time required to generate images for the reconstruction of three-dimensional flow structure. In other words, the structure being analyzed must be “frozen” during the time the images are generated.

The essential difference between computer tomography and high-speed filming consists in that the former enables one to obtain three-dimensional information about the structure and to analyze the process at different observation angles, thereby providing for greater depth and higher quality of analysis of the processes involved.
The visualization methods used in analyzing the flow structure have been known for several decades, with a continuously increasing share of the optical and laser-optical techniques employed to investigate the structure of turbulent flows. These include the laser methods for two-dimensional analysis of flow structure [5, 6, 8], the PIV and PTA methods [2–5, 10–14], and holographic methods [15]. Note that the practical realization of these methods is associated with serious technical difficulties and financial costs. It is especially difficult to produce a three-dimensional structure; as a rule, this requires much time and involves a partial loss of input information.

A general impression of the possibilities offered by the methods of flow visualization is given in [16], where the methods of light sheets (slices) moving along a normal to these sheets are described for studying the three-dimensional development of the structure of turbulent jets. Veret [17] describes the methods of visualization of the vortex flow structure emerging behind an aircraft model at subsonic velocity and behind a delta-wing model of different configurations [18]. Prenel et al. [19] made an attempt at producing qualitative results for a delta wing by means of photography. The scanning of flow was performed by a plane laser beam with the aid of a mirror secured on the frame of a galvanometer whose angular position was synchronized with the camera shutter. By varying the orientation of the laser sheet, one could obtain information about different stages of space development of flow. The equipment described in [20] provides for a high time resolution during optical scanning of flow using a high-speed camera. The scanning distance was 150 mm, with the scanning time of 3.7 ms and the number of images being processed equal to 30. Some images were transformed to digital form and, with the aid of dedicated software, reconstructed to a three-dimensional representation of the flow being investigated. The short time of measurement enabled one to better “freeze” the structure and, thereby, obtain a higher quality flow pattern.

A special visualization scheme (light sheet in the form of a cone cylinder) was developed by Porcar et al. [21] for symmetrically rotating structures, which enabled one to photograph the lines of fan flow.

Hesselink and Pender [22] describe the equipment which permits one to visualize vortex formations behind a cylinder, transform the resultant patterns to holographic images, and perform the subsequent three-dimensional computer reconstruction of those vortex formations.

The distinguishing features of recent studies in the field of practical implementation of methods of optical tomography include the use of a laser as the light source, production of images with the aid of a digital CCD videocamera, and digital processing of images with their subsequent computer processing and analysis [23–35].

An analysis of available literature reveals that, as regards the development of advanced optical methods for investigation of flows, no possibilities are observed for simple and relatively inexpensive development and implementation of equipment for optical tomography.
which would provide relatively high time and space resolution as applied to objects of experimental aerohydromechanics.

This paper gives the general concept of constructing a laser tomographic system enabling one to realize a space resolution starting from 0.1 mm between successive light sheets and a time resolution up to 226 images per second. Also given are the algorithms for identification of the sought objects and their reconstruction and representation in three-dimensional space using standard software packages.

2. IMAGING AND RECONSTRUCTION OF IMAGES IN THREE-DIMENSIONAL SPACE

The laser light-sheet techniques for flow visualization is based on the scattering properties of optical inhomogeneities moving along with the flow. If parti-
cles are moving in a flow, differences are observed in their space concentration as a result of the effect of the transport processes. In a laser-illuminated light sheet, different intensities of light scattered by optical inhomogeneities are observed. This enables one to visualize the processes occurring in the flow and use video equipment for imaging. Figure 1 illustrates the principle of three-dimensional optical scanning of the flow being investigated.

The intensity of light scattered by optical inhomogeneities defines the choice of the method for recording this light. At present, preference should be given to CCD videocameras, first of all, because of the absence of afterglow, which improves considerably their dynamic properties. The use of standard analog videocameras limits the maximum speed of recording (frame frequency) which, in accordance with the TV standard, cannot exceed 50 Hz. In this respect, preference should be given to digital cameras which enable one to film processes at a rate of 200 Hz and higher, although these cameras are still much more expensive than the conventional ones. Note that, given a constant frame frequency, a high space resolution is associated with a low time resolution and, vice versa, a high time resolution is associated with a low space resolution. In other words, in order to “freeze” well a structure of length L, one must scan the space being investigated as quickly as possible, this causing the need to reduce the number of light sheets (frames) to be analyzed. On the other hand, an increase of space resolution is associated with an increase of the number of light sheets to be analyzed (with a reduction of the spatial distance between the neighboring images being analyzed; this, in turn, leads to an increase of the total scanning time T.

The following simple relations are valid for the scanning region:

\[ T = \Delta t n + t_1 (n - 1) = (n - 1)(\Delta t + t_1) \],

\[ L = \Delta x n + d_1 (n - 1) = (n - 1) \Delta x \],

\[ T = \frac{L}{V_{\text{scan}}} = (n - 1) \frac{\Delta x}{V_{\text{scan}}} \],

where \( \Delta t \) is the exposure time of the videocamera, and \( V_{\text{scan}} \) is the rate of scanning. The rest of the designations are given in Fig. 1. Figure 2 shows the main stages of operation of the system of optical tomography (SOT).

### 2.2. Contouring (Segmentation)

The process of assigning a certain value of luminance threshold with a view to identifying the portions of image of interest to us, whose luminance exceeds this assigned threshold, is referred to as contouring or segmentation. This threshold value is selected arbitrarily and is of decisive importance from the standpoint of correct choice of the contours of flow (contouring). With the luminance resolution of, say, 8 bit, the contouring threshold may be selected in the range from 1 to 255. Figure 4 illustrates the process of segmentation for different threshold values of luminance.

The process of selecting the contouring threshold is not yet automated, and this threshold needs to be corrected for every new series of images, which delays the final results. Note that this process may now be automated if one develops multistep smart algorithms of search for the optimum contouring threshold as applied to a concrete series of images.

Standard computer codes for image processing provide for the choice of desired contour proceeding from various criteria, for example, the choice based on the length of contour. Therefore, if several contours are obtained in the process of segmentation, as is shown in Fig. 5, the desired contour is selected using the standard algorithms of image processing.
2.3. Vectorization of Contour (Segment) Boundaries

By vectorization is meant the determination of the coordinates of contour boundaries, which correspond to the contours of the real flow pattern. In terms of informatics, this means the transformation of the image data format to vector form. From the standpoint of the quality of further reconstruction of the three-dimensional surface, the optimum choice of the number of points of scanning the contour is of importance. If the number of points is small, further reconstruction is associated with the loss of information about the fine structure of flow surface (Fig. 6a). With a larger number of such points (Fig. 6b), the processes associated with further implementation of the SOT are decelerated (Fig. 2).

2.4. Simulation of Three-Dimensional Surface and Realistic Representation of Flow Structure

As was already mentioned, when the SOT is implemented, one must, first, obtain a series of images of flow structure for a period of time during which the structure remains invariant ("frozen"); second, reconstruct the shape and surface of the entire flow within the space being observed from individual contours of flow section; and, third, represent realistically in three-
dimensional space the structure being analyzed which could be observed at different angles of view. In Fig. 7, the analysis of the structure of a free jet is used as an example to illustrate successive working steps in the implementation of the SOT. Figure 7a is a series of successive pictures of a jet taken by a digital videocamera and corresponding to the real motion of the light sheet in the space being observed. The coordinates of the flow structure contours, obtained from individual light sheets, are further transformed to the data format for representing images in three-dimensional space using standard CAD software (Fig. 7b), this corresponding to the real flow pattern. The next step involves the use of standard spline-interpolation software to reconstruct the entire surface of the flow structure from individual contours (Fig. 7c). The last step is the generation of a realistic image of the structure being analyzed and involves the use of standard CAD computer codes.
Fig. 10. The scheme of hardware and software support of the SOT.

Fig. 11. The optical scheme of the SOT and LDA.

which enable one to realize and enhance the spatial perception of the structure being observed (shadow coloration depending on the position of the virtual light source, reflectivity and refractive index of the surface being observed, degree of its transparency, background illumination, etc.) (Fig. 7d). In so doing, the structure being analyzed could be observed on a display screen in three-dimensional space at different angles of view.
3. EXPERIMENTAL SETUP

3.1. Optical Scheme

The SOT was implemented according to the scheme given in Fig. 8. A cylindrical lens was used to transform a laser beam into a two-dimensional plane light sheet (y = z) which was reflected from a rotating mirror and moved in the x-direction normal to its plane to form a three-dimensional region to be scanned. The optical scheme is given in detail in Fig. 9.

The cylindrical lens (F = 5 mm) was mounted on the laser optical axis and transformed the laser beam into a plane horizontal beam, which then hit the mirror secured on the shaft of a step motor and deflected in the vertical plane to change its spatial position around the y-axis and scan the volume being investigated in the direction of the x-axis. The flow being investigated was directed in parallel with the x-axis normally to the plane light sheet. As the angular position of the rotating mirror varied, a space of $25 \times 25 \times 12$ mm$^3$ was scanned. The step and speed of the step motor could be varied in a wide range, which provided for the desired variation of the time and space conditions of the experiment. The space step could be varied within 0.1–3 mm, which corresponded, for the length of the investigated space of 22 mm, to generation of 7 to 210 images during a single series of scanning the volume being investigated. The step motor provided for the immobility of the light sheet during the time of exposure; this resulted in a considerably improved quality of the images but called for strict synchronization of the moment of halting the engine with the time of exposure of the videocamera and the spatial position of the light sheet in the flow being investigated. The basic geometric correlations are given in Fig. 9. Given the videocamera speed of 200 images per second and the distance between the neighboring light sheets of 1.0 mm, one can readily obtain the time of scanning the entire flow portion.
being measured, which is 125 ms; therefore, the flow must be "frozen" during this time in order to produce correct results. The minimum scanning time during the experiments was 70 ms (with the filming frequency of 100 Hz in the triggering mode and seven images in a series).

Note the lack of parallelism of light sheets in the employed optical scheme of SOT, which may be regarded as a shortcoming.

3.2. Hardware Support

A series of images was filmed by a CAD1-256 digital CCD videocamera (Area-Scan) manufactured by DALSA with the resolution of 256 × 256 points. The on-line observation of video pictures made possible a preliminary estimation of the quality of received images. The appropriate videosignal from the camera (Fig. 10) was delivered to the digital interface video-card of a PC with the working memory of 128 MB. The high rate of exchange of information between the interface devices and PC (up to 90 MB/s) provided for the real-time storage of information. The interface included a standard IC-P-2M base module and a digital AM-DIG receiving module operating jointly to receive, match, and exchange information between the videocamera and PC. The step motor and videocamera were synchronized with the aid of a pulse generator, by varying whose frequency one could preset different speeds of the step motor and corresponding frequency of videofilming. When a clock pulse was delivered, the step motor turned one step, and, simultaneously, the same signal triggered the receiving module of the interface device for storing the arriving image. This arrangement enabled one to match the time parameters of videofilming with the space parameters of light sheet and flow being investigated.

3.3. Software Support

The OPTIMAS standard computer codes were used for receiving, processing, and analyzing images, and the AutoCAD computer codes were used for the reconstruction of structure in three-dimensional space and for its realistic volume representation (Fig. 10).

3.4. Subject of Investigation

The investigation was concerned with a free jet of air, into which oil particles 0.5–2 mcmb in diameter were injected. This main jet could be deformed ("drift") under the effect of an additional transverse flow (Fig. 11). The extent of deformation (drift) was defined by the ratio between the velocities of the main, $U$, and transverse, $V$, flows. The LDA technique was used to additionally measure the axial component of the velocity of main flow at different distances from the channel exit section in order to determine qualitatively the main kinematic parameters of the free jet being investigated (Fig. 12). For the given boundary conditions, the velocity varied within 0.01–0.2 m/s, which corresponded to the Reynolds number values $Re = 30$ to 600. For small values of the Reynolds number, laminar flow persisted in the jet over a distance of several millimeters after leaving the channel. With a velocity exceeding 0.7 m/s, the laminar flow mode deteriorated immediately at the
channel exit. The degree of turbulence of the main flow, measured using the LDA technique, depended considerably on the kinematic parameters of transverse flow.

4. EXPERIMENTAL RESULTS

Figure 13 gives, by way of example, a reconstructed three-dimensional image of an undeformed jet (the transverse flow velocity $V$ is zero) leaving a three-millimeter round channel (bottom right). In the process of scanning, the jet remained “frozen”; i.e., in this case the time of measurement was much less than the time characteristic of the processes of deformation (distortion) of a jet issuing from the channel. The distance $d$ between the neighboring light sheets varied from 0.2 mm to 1.8 mm, which corresponded to the variation of the number of images being analyzed from 115 to 13 and had almost no effect on the type and shape of reconstructed three-dimensional image of the jet. In subsequent experiments, $d$ amounted to 1.5 mm. Figure 14 illustrates a reconstructed jet with inadequate time resolution, that is, with the processes of deformation of the jet being faster than its analysis (the flow was not sufficiently “frozen”).

In order to have a spatial idea of the flow structure, as well as to visualize the latent information about the structure of the jet surface, one could observe the structure being investigated on a display screen at any solid angle. Figure 15 gives space images of one and the same jet deformed by transverse flow when viewed at different angles. The transverse flow causes a deformation of the cross section of the main jet issuing from a round channel. By “turning” the jet, “rotating” it in three-dimensional space, one can obtain additional information about the jet parameters, the physics of emergence of turbulent phenomena, and so on. The emerging waviness of the surface points to the signs of axial instability of the jet. Figure 16 illustrates the

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**Fig. 15.** Images of a deformed jet, corresponding to different directions of observation.

**Fig. 16.** Changes in the surface structure of a free jet for different velocity ratios $k_i$ between the main and transverse flows.
structure of a free jet for different ratios of the velocities of transverse and main flows \( k_i = V/U \). Also observed in Fig. 16 is some instability of the jet surface, which later leads to its disintegration. In Fig. 17, the same jet as in Fig. 16 is shown at a different angle of observation. One can see how the angle of efflux of a free jet from the channel varies as the transverse flow velocity increases, i.e., as \( k_i \) increases. At the same time, the “waviness” of the structure increases, and high-frequency “traces” emerge of the effect of transverse flow, which leads to an earlier subsequent “disintegration” of the jet.

5. CONCLUSION

This study was aimed at developing an optical system that would enable one to visualize the flow structure being investigated, store it with the aid of optoelectronic means for reception and conversion of information, reconstruct the structure three-dimensionally, and represent it in such a manner that it could be analyzed in three-dimensional space at any angles of observation. For this purpose, the investigated volume was optically scanned, and the emerging sequences of optical patterns were filmed by a digital videocamera. The obtained digital information was transferred to a computer, processed, and converted to a data format convenient for further application of standard software packages for volume reconstruction of turbulent structure and its realistic representation. The results are indicative of the emergence of a new tool for the investigation of flow structure, although one must note that the obtained results are qualitative, primarily because of the arbitrary (subjective) choice of the luminance threshold in the process of selecting the contours of video images (see Section 2.2). The phase of volume reconstruction and development of a realistic three-dimensional image presents no serious problems in view of the currently available computer software. In order to obtain quantitative experimental data, one must estimate and compare the errors produced by the use of different interpolation techniques in reconstructing the three-dimensional surface of flow structure. The use of standard software packages made it possible to obviate the rather complicated and labor-consuming stage of developing separate software and to considerably reduce the time required for the development of SOT, with a fairly high quality of the end results. We hope that the herein-described fundamentals of laser optical tomography and the practical results, as applied to the investigation of flow structures, will provide for
more extensive uses of advanced optical methods in the field of experimental aerodymomechanics.

REFERENCES


