Laser Streak Velocimetry for Two-Dimensional Flows in Gases

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A velocity measuring technique, Laser Streak Velocimetry (LSV), has been developed for two-dimensional flows in gases. A high power laser beam is formed into a thin sheet to illuminate a seeded flow in a two-dimensional plane around a body. Short exposure streak photographs are recorded of the seed particles as they traverse the light sheet; the two-dimensional velocity vector is then computed from the length and direction of each streak. The validity of this technique was demonstrated by measuring the velocity profile in the boundary layer of a flat plate which was found to agree within 4% of theoretical predictions. To demonstrate the application to nonsteady flows, a mapping was made of the nonsteady vortex shedding of low Reynolds number flow past a circular cylinder. Because of current interest in low speed aerodynamics, the LSV method was also used to obtain the velocities over the surface of a 60° delta wing at 15° angle-of-attack, and results were compared to a related theory. Improvements and future developments of LSV are discussed.

I. Introduction

THE science of aeronautics has always been plagued by the somewhat intangible qualities of air and the problems in measuring these qualities without disturbing the flow. The common methods for velocity measurements, such as pitot tube and hot wire systems, are accurate enough but require probes to be inserted, invariably disturbing the flow.[1] Since these methods give point-by-point measurements, they require steady flow and a large number of measurements to accurately cover the entire flow field.

Laser doppler velocimetry (LDV) increases the accuracy of measurements and negates the need for insertion of probes into the flow.[2] While there are LDV systems with a limited scan rate, most are restricted to point-by-point measurements.[3] A method of simultaneously measuring velocities over large areas and volumes is clearly needed for such applications as nonsteady vortex flows.

The advent of lasers permitted the development of a refined streak technique for measuring simultaneous velocities over large areas. The new method retains the simplicity of conventional streak techniques, but improves considerably upon their accuracy and usefulness. It was used to measure a known flow, i.e. the boundary layer on a flat plate, so that results could be compared to theory. The vortex shedding behind a circular cylinder at low Reynolds numbers was also measured to demonstrate applications to nonsteady flows. Finally, the flow over the top of 60° delta wing was examined because of current interest in low speed aerodynamics.

II. Laser Streak Velocimetry

The technique presented here, Laser Streak Velocimetry (LSV), involves the use of a high power beam that is transformed into a very thin sheet of light. The light sheet can be placed in any orientation around an aerodynamic body in a wind tunnel. Very small particles are introduced into the tunnel, and streak photographs are taken of the flow of the particles around the body. The length of the streak made by each particle during a known exposure time is a measure of its velocity in the two-dimensional plane of the light sheet.

The beam from a 3.5 W cw argon laser, operating in a single radial mode, was formed into a thin sheet by means of a cylindrical lens followed by spherical lens. The cylindrical lens was mounted on a mechanical rotator to permit easy and precise angular orientation of the light sheet. The light sheet was approximately 0.3 mm thick and 25 cm wide inside the test section.

A low speed, simple wind tunnel, built especially for this research, was drawn down by a motor and fan assembly that was isolated from the tunnel and laser to minimize vibrations. The wind tunnel inlet had a horizontal contraction that varied from 20 cm at the entrance to 10 cm at the test section. No vertical contraction was included for simplicity. Straws were packed into the inlet just upstream of the contraction to collimate the flow and remove eddies.

The aerodynamic models were mounted in a 10×10 cm glass test section on stings attached to a translation stage which permitted precise angular and vertical positioning of the model. The outlet section of the wind tunnel was connected to the motor and fan assembly by a flexible 10 cm diameter hose.

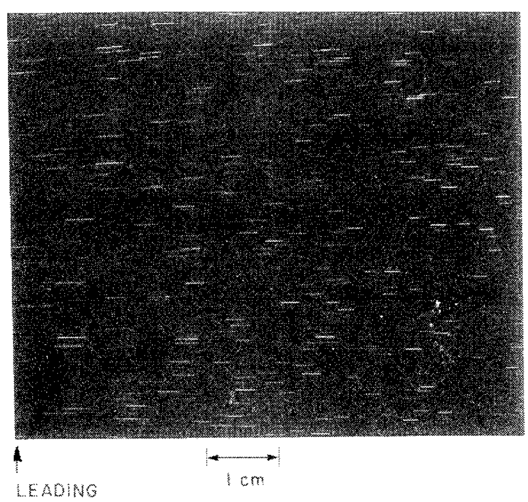

Fig. 1 Streak photograph of flow 3.0 mm above surface of flat plate.

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The camera was located on an adjustable mount above the test section. High speed (ASA 3000) film was necessary to meet the exposure constraints of the measurements described in this paper. The current setup is restricted to flows of less than 10^3 cm/sec since we use a mechanical camera shutter whose fastest speed is 1 msec.

Talc particles of about 10 μ in diameter were dispersed into the tunnel by manually squeezing a plastic bottle. This method introduced very little turbulence into the tunnel and allowed good control of the particle concentration. Particles of this size can be expected to follow flows up to medium subsonic speeds. No effort was made to make the particles smaller or more uniform in size and shape; however, the larger particles were allowed to settle out before they entered the tunnel.

An aerosol of approximately 5 μ water particles was tested and found to be inferior to talc for the arrangement used. The transparent water droplets were relatively weak light scatterers and were also difficult to introduce into the tunnel without creating turbulent eddies. The high water vapor content of the aerosol caused blooming on photographs taken at laser powers over 2 W, thus washing out the data in the streaks.

III. Measurements Using LSV

A. Measurement of Velocities in a Boundary Layer of a Flat Plate

The boundary layer on a flat plate was measured since it is a classical problem with a well known theoretical solution.[4] This permitted easy comparison of our LSV data with theoretical predictions.

In this measurement, the light sheet was aligned parallel to the freestream flow. The exact alignment was determined by rotating the sheet until the longest streak lengths were observed. The 10×15 cm flat plate was then positioned parallel to the light sheet and adjusted vertically by the translation stage. Streak photographs of the particles in the flow were made at intervals of 0.2 mm above the surface of the flat plate up to 5 mm. Typical results are shown in Fig.1, which is a photograph made 3 mm above the surface. The photographs covered the central 6 cm of the plate, and extended 8 cm back from the leading edge. It can be noticed that the lengths progressively shorten downstream from the leading edge. The longer streaks near the leading edge indicate that the boundary layer is very thin in that region, while the shorter streaks further downstream indicate lower velocities and thus a thicker boundary layer.

A plot of the nondimensional velocity U/U_∞ measured as a function of the nondimensional height η above the flat plate on a line 2.5 cm from the leading edge is shown in Fig. 2. This downstream distance was chosen because it was where theory predicts the boundary-layer thickness should be 5 mm.[4] The length of the error bars on the data correspond to the difference between the longest and shortest streaks in the area measured on each photograph. It can be noticed that the largest deviations from theory occur in measurements taken within 1.2 mm from the surface. This can be partially attributed to shortening of the streak lengths due to particle deposition on the surface of the flat plate. In addition, when there are large vertical velocity gradients, for example near the base of the boundary layer, we would expect a greater distribution in streak lengths.

The remainder of the measurements agree closely with the theoretical curve, especially if only the longest streak lengths are used. When only the longest streaks are considered, the results match theory to within 4%. The increased accuracy of the longest streaks is to be expected since no mechanisms exist to cause the particles to move faster than the local fluid velocity, but inertia, particle deposition, and particles exiting the sheet can cause streaks to shorten. Streak lengths could be measured to within 5% by simple visual means.

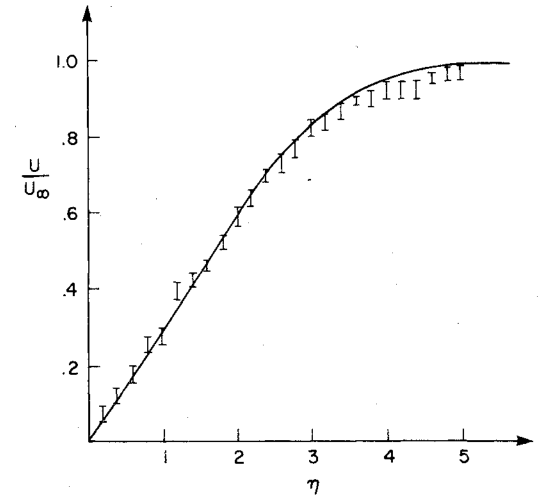

Fig. 2 Measurements of vertical velocity profile in boundary layer of flat plate – solid curve is theoretical.

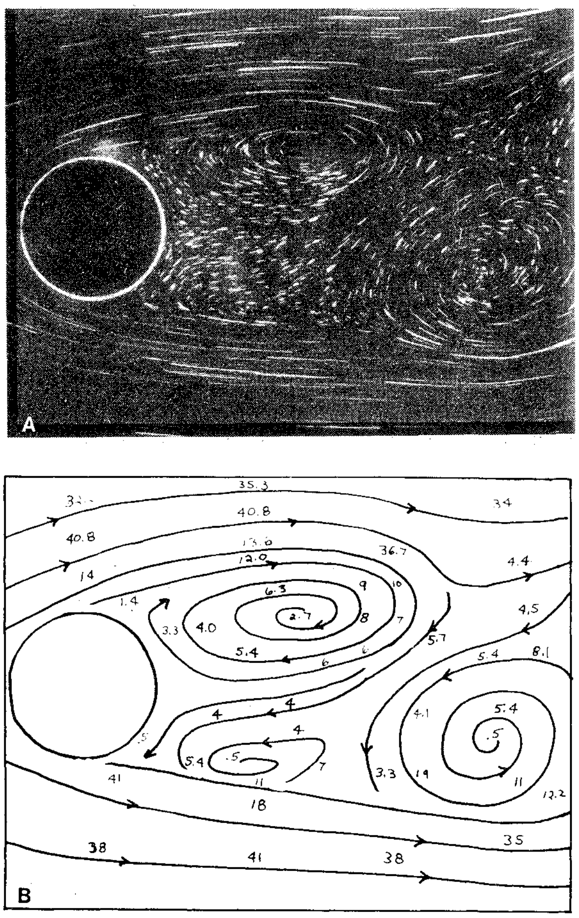

Fig.3 A) Photograph of nonsteady vortex shedding behind circular cylinder, $Re = 270$, and B) velocity mapping of Fig. 3A.

B. Measurement of Velocities in Wake of Circular Cylinder

The flow around a circular cylinder is basic to fluid mechanics, nevertheless, analytical treatments of the wake have been formulated only up to a Reynolds number of 100.[5] At Reynolds numbers over approximately 100, the wake becomes unstable and vortices from a Karman vortex street that is recognizable up to $Re \cong 2500$.[6] The LSV method was used to map the velocities in the unsteady vortices immediately downstream of the circular cylinder.

A 1.6 cm diameter circular cylinder was placed vertically in the test section and held in place with beeswax. The light sheet

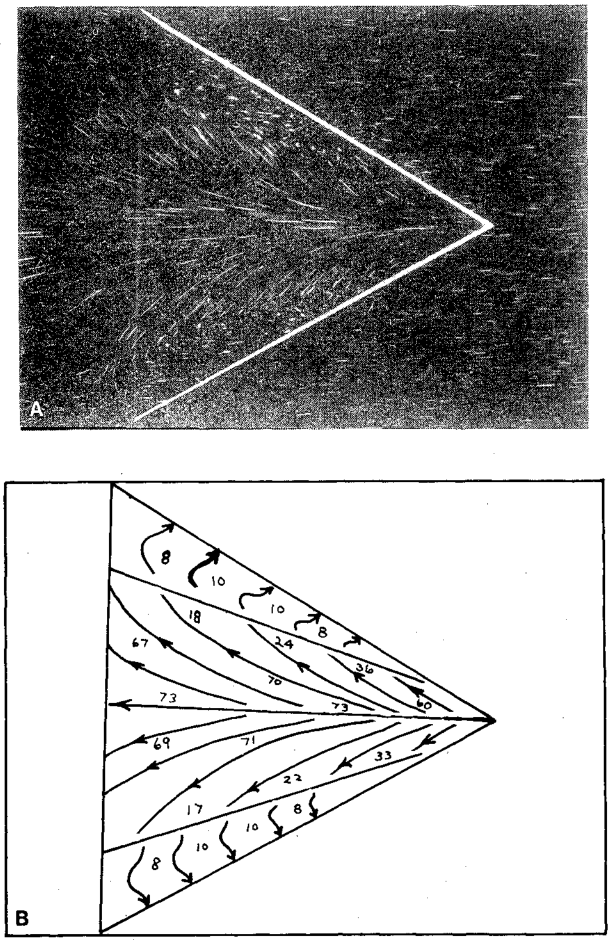

Fig. 4 A) Photograph of flow over top of 60° delta wing at 15° angle-of-attack, and B) velocity mapping of Fig. 4A.

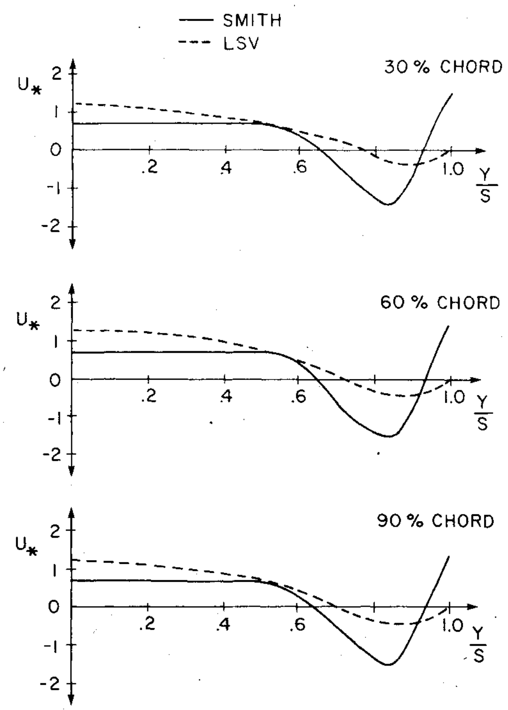

Fig. 5 Measurements of longitudinal velocity on upper surface of delta wing at 30%, 60%, and 90% chord points. Solid curve is theoretical.

was aligned parallel to the freestream flow, and photographs were made from above the cylinder.

Figure 3A is a photograph of the vortex shedding at $Re=270$. It can be noticed that two vortices have shed, and a third is forming near the bottom rear of the cylinder. Figure 3B is the mapping of the velocities as measured from the photograph.

Unfortunately, there is no theory to compare with the results of the unsteady vortex flow. Indeed, previous velocity measuring methods were unable to measure the instantaneous velocities in this type of unsteady flow. LSV provides the only method at present of measuring such velocities.

C. Measurement of the Flow Over a Delta Wing

There is current interest in the low speed characteristics of delta wings since even high performance aircraft must operate in the low speed regime for takeoff and landing. The flow over a 60° delta wing at $\alpha=15°$ was measured with LSV, and results are compared to an analytical treatment of a low aspect ratio delta wing.

A 60° delta wing of 5.1 cm chord and 0.05 cm thickness, having sharp, beveled edges, was mounted on a sting. The light sheet was set at 15° angle-of-attack, and the delta wing was aligned parallel to the sheet. The camera head was tilted 15° so that the focal plane remained parallel to the light sheet. Photographs were made at intervals of 0.2 mm up to 5 mm from the upper surface of the wing at a Reynolds number of 3560.

The flow at 0.2 mm above the surface of the wing is shown in Fig. 4A. The high speed central core diverges to the two attachment lines of the leading edge vortices. The area outboard of the attachment lines is the separation region and contains reverse flow toward the leading edges. At this Reynolds number, the reverse flow remains laminar and attached until the leading edges.

The velocity mapping of the data from Fig. 4A is shown in Fig. 4B. The velocities in the central core are found to decrease laterally up to the attachment line which is also the line of zero longitudinal velocity on the upper surface. If the flow were conical, the velocity along any radial line moves from 77% of the semispan at the 30% chord point to 70% of the semispan at the 90% chord, making the flow nonconical. The reverse flow region is characterized by velocities of 10 cm/sec.

The nondimensional longitudinal velocity U_* vs the distance on the semispan y/s as plotted in Fig. 5 for the 30%, 60%, and 90% chord points. Also shown is the analytical curve derived by Smith, based on an iterative scheme to solve the equations of motion.[7] The experimental results do not quantitatively agree with Smith's predictions, but the shapes of the curves are approximately the same. The largest difference occurs in the magnitude of the reverse flow in the separation region. These differences may be attributed to several factors. Smith assumed conical flow in his treatment, but the experimental results, as mentioned previously, clearly show that the flow is not strictly conical. In addition, Smith used slender body theory and assumed a low aspect ratio wing of zero thickness. Even though our experimental wing had medium aspect ratio and a finite thickness, our results substantially support Smith's treatment.

IV. Discussion

The primary advantage of LSV is the simplicity of the method itself. There is no complicated alignment of optics or electronics, as in LDV, nor is there a restriction on the size of the area measured. A laser and camera are the basic components, and the system can be incorporated into most existing wind tunnels. Unlike other velocity measuring schemes, LSV can be used to measure, as well as visualize, steady or unsteady two-dimensional flows. The streak photographs are a dramatic, permanent record of the instantaneous flow, making LSV a valuable tool for the classroom as well as the research laboratory.

The LSV setup, although simple and effective is not without its limitations. In common with any scheme using particle tracers, the fidelity with which the particles follow the flow is a function of particle size, generally the smaller the particle, the faster it returns to local fluid velocity after the velocity changes. A study by Mazumder and Kirsch[8] showed that 0.2 μ unit density spherical particles followed subsonic turbulent frequencies up to 100 kHz with 98% fidelity. A system is therefore needed to generate and disperse uniform, approximately 1 μ, spherical particles to increase accuracy.

To reduce undesirable reflections that occur when the light sheet strikes the surface of a model, it is possible to use laser induced fluorescence rather than elastic scattering. We conducted tests in a wind tunnel with aerosols of Rhodamine 6G in water, that were excited at 5145 Å. When the flow was viewed through a filter, there was almost total blockage of the laser light, yet streaks from the fluorescent aerosols could be clearly observed. Further tests should be conducted to determine feasibility and advantages of fluorescent particles for LSV.

The measurements of individual streak lengths need not be a subjective matter. The length of each streak can be designated as the distance between the half power points as measured by a microphotodensitometer.

In the case of large wind tunnels, the separation between the model and the camera may be great enough to require telescopic lenses for photographing the flow. The width of individual streaks will clearly be determined by the quality and diameter of the optics, as well as the particle size and film resolution. Another problem in large wind tunnels is the production of a thin sheet over large distances.

The application of the LSV method to high speed flows would require exposure times of less than 1 msec, which is not easily attained with mechanical shutters. One possible solution is to leave the camera shutter open and pulse the laser, making the length of the pulse determine the exposure time. The laser energy needed per pulse is about 4mJ/cm^2 for adequate film exposure in our present set-up.

An alternate way of determining particle velocities is to use very short laser pulses repeated at known intervals. If the pulses are short enough so that the particles do not streak on the photograph the particle velocity can be determined by the distance between consecutive images of the same particle. This scheme would also permit the tracing of the complete path of a single particle through the flow.

For the case of three-dimensional nonsteady or turbulent flows, the entire flow volume must be measured in a very short time. This can be accomplished by scanning a pulsed sheet and recording the images on high speed movie film. Reduction of the data from such a scan can be simplified by replacing the photographic film with electronic image sensing devices. Clearly, there are several areas which can be pursued to further improve the accuracy and usefulness of Laser Streak Velocimetry.

V. Conclusion

LSV has been shown to be a simple and accurate method of simultaneously measuring velocities over a large area. It is particularly well suited for steady and nonsteady two-dimensional flows.

The velocities in the boundary layer of a flat plate were measured by LSV and found to agree within 4% of theory when only the longest streak lengths were used. The nonsteady vortex shedding behind a circular cylinder was photographed, and a mapping of the velocities within the vortices was constructed. The velocities over the top of a 60° delta wing were measured and compared to a related analytical treatment by Smith.

The primary advantage of LSV is the simplicity of the setup and its operation, coupled with reasonable accuracy and adaptability. Some of the limitations of LSV, such as particle size and uniformity, can be overcome by the design of an automatic generator and disperser of unit density, spherical, one micron particles. A pulsed laser would permit the extension of LSV to velocities approaching sonic, while high speed scanning of a pulsed sheet can map three-dimensional, nonsteady flows.

LSV has been shown to be an effective research tool, and extensions of the present method should be pursued to explore the full potential of the technique.

Acknowledgments

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