AIAA 80-0421R

Visualization of Transition in the Flow over an Airfoil Using the Smoke-Wire Technique

Stephen M. Batill* and Thomas J. Mueller†
University of Notre Dame, Notre Dame, Ind.

The smoke-wire technique was used for visualization of the transition of the free shear layer associated with the laminar separation bubble of a NACA 66_3-018 airfoil section at low Reynolds number (Re_c = 50,000-120,000). The smoke-wire technique allows for the introduction of fine smoke streaklines into the flowfield through the electrical resistive heating of a very fine wire which has been coated with oil and which is located upstream from the leading edge of the airfoil section. Streakline data were collected using both high speed still and motion picture photography.

Introduction

THERE has been a great interest, throughout the history of aerodynamics, in making flow patterns visible. Unlike other measurement techniques, which are limited to measuring flow conditions at discrete points within the flowfield, visualization techniques are capable of yielding a macroscopic, though in many cases qualitative, "picture" of the overall flowfield. In most cases, this is done without the introduction of probes, which could alter the phenomena being studied, into the flowfield. The use of smoke in wind tunnels began near the end of the nineteenth century[1] and has subsequently been developed into an important research tool.[2] The method cited in Ref. 2 has probably become the most successful and commonly applied of the smoke visualization techniques. This method makes use of rather large quantities of smoke which are produced outside of the wind tunnel and introduced into the tunnel either upstream of, near the inlet or setting chamber, or near the test section. Although this method has been used to study many complex flow problems, there are fundamental flow phenomena which require the ability to produce small but discrete smoke filaments (streaklines) and to be able to locate the filaments accurately within the flowfield so that small scale details may be studied.

The smoke-wire technique, developed by Raspet and Moore in the early 1950's and subsequently improved[3] and extended,[4,5] is capable of producing very fine smoke filaments and can be used to study the detailed structure of complex flow phenomena. According to Cornish,[6] this technique may have originated with one of Prandtl's students. The "smoke" is produced by vaporizing oil from a fine ($\simeq$0.1 mm) wire by the use of resistive heating. The technique was initially applied to the measurement of velocity profiles in a boundary layer. Much of the present smoke-wire capability is due to the system developed by H. M. Nagib and his co-workers.[7,8] Recent applications have included the investigation of the large eddy structure in turbulent shear flows.[7-10]

The smoke-wire technique is limited and, fortunately, ideally suited to applications where the Reynolds number based on wire diameter does not exceed 20. For practical applications, this requires wind tunnel speeds on the order of 2-6 m/s.

The present paper is a report of the apparatus and techniques used in applying the smoke-wire technique to the study of the laminar separation bubble and transition on a NACA 66_3-018 airfoil section. This particular phenomenon presents some unique challenges which indicate the need for flow visualization and the smoke-wire is the ideal candidate. It can be used to study the physics of this complex flow phenomenon in regions of slow, recirculating flow where other measurement techniques such as hot-wire and pressure transducers are very difficult to use.

Smoke-Wire Technique

The method consists of a fine wire positioned in the flowfield, coated with oil, and heated by passing an electrical current through the wire. As the wire is coated with the oil, small beads of the oil form on the wire and at each of these beads the smoke filaments originate when the wire is heated. Cornell[11] conducted an extremely thorough study of materials used in "smoke" generation for flow visualization and he indicated the particles formed in this manner should be classified as a vapor-condensation aerosol. They are actually small liquid particles ($\simeq$1 μm diameter) and not products of a combustion process or solid particles. Though the product is not smoke in a strict definition of the term, it will be referred to as such in this paper.

As in most flow visualization studies, the actual application of the visualization method depends upon the phenomena being studied. In the series of experiments documented in this paper, the detailed structure of the laminar separation bubble which forms near the leading edge of airfoil sections at low Reynolds numbers was of major interest. The tests were conducted in one of the University of Notre Dame's low turbulence subsonic, indraft wind tunnels. A wing model with a 0.25 m chord and a 0.40 m span with a NACA 66_3-018 airfoil section was fitted with end-plates and mounted in a 0.6 m$\times$0.6 m square cross-section test section. A schematic representation of the model and end plates is shown in Fig. 1. Also in Fig. 1, the two smoke-wire locations which were used are shown. The horizontal wire (A-A) was used to introduce a sheet of fine smoke streaklines in a plane along the span of the airfoil model. The wire was located 65 mm forward of the leading edge of the airfoil and was parallel to the leading edge. The vertical location of the wire was adjustable using a screw-track device attached to the outside of each end-plate. This allowed for accurate positioning of the sheet of smoke relative to the airfoil. The vertical wire (B-B) was used to produce a sheet of streaklines in a plane normal to the leading edge of the airfoil. This wire was located 430 mm forward of the leading edge of the airfoil.

Smoke-Wires

A number of different wires were used in the development of the technique for this experiment. These included 0.025,

Presented as Paper 80-0421 at the AIAA 11th Aerodynamic Testing Conference, March 1980; submitted April 8, 1980; revision received Oct. 6, 1980.

*Assistant Professor. Member AIAA.

†Professor. Associate Fellow AIAA.

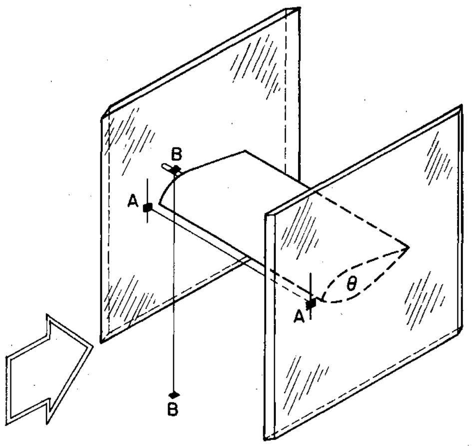

Fig. 1 Schematic of wind tunnel model end plates, and wire locations.

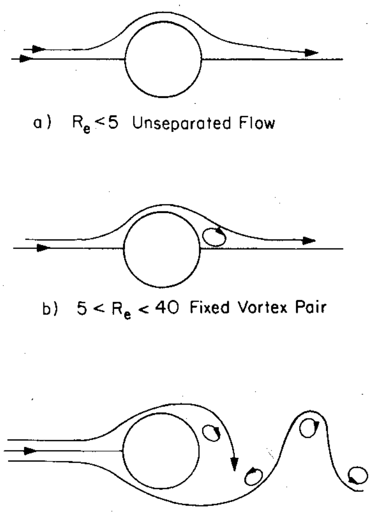

Fig. 2 Wire wake variation with Reynolds number.

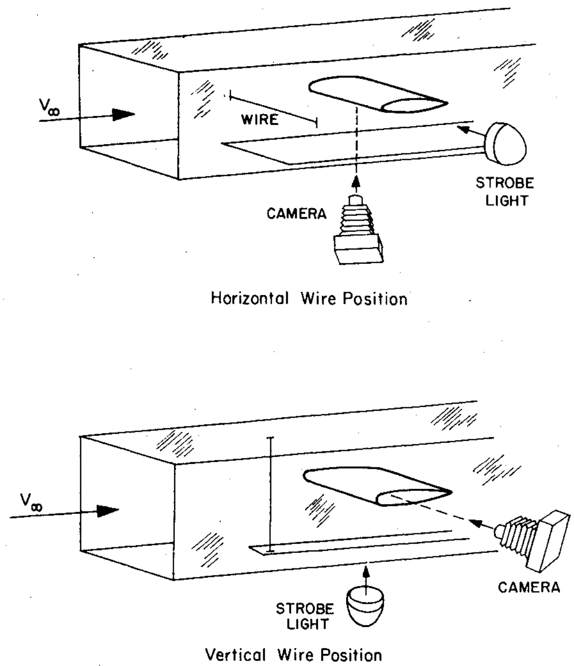

Fig. 3 Wire, camera, and light locations for planform and profile views.

0.076 and 0.152 mm (0.001, 0.003 and 0.006 in.) diameter stainless steel and tungsten wires. The strength, resistive heating characteristics and size are all important factors in choosing the "best" wire for a given application. Since, as in most flow visualization experiments, any adverse influence on or disturbance of phenomena being studied must be minimized, the wire wake influence on the boundary layer phenomena being studied must be determined. For this reason, the local Reynolds number based on wire diameter, thus the wire wake, is an important consideration. Figure 2 shows the type of wake structure associated with a right circular cylinder as a function of cylinder Reynolds number based on cylinder diameter, Re_d.[12] Figure 2 indicates that an ideal situation would require Re_d to be less than 5, but, in practice, this is quite difficult to achieve. For this work, a Re_d less than 20 was maintained and, as will be discussed later, this was quite acceptable.

As the wire is heated it expands and sags which is not desirable if accurate placement of the smoke streaklines is required. Therefore, the wire was pre-stressed so that, when heated, there was no noticeable sagging. This required a pre-stress level of approximately 1.03×10^9 Pa (1.5×10^5 psi) for the stainless wire. Since this is quite near the yield stress for the wire, it was important that once it was stressed it was handled carefully. Some attempts were made to maintain tension in the wire by spring loading, but these were not as successful as the simpler pre-stressing between fixed supports.

The size of the wire also dictates the amount of oil which could be placed on the wire and, thus, the length of the streaklines for a given wire temperature. The finest wire tested, the 0.025 mm, proved to be unsuitable because it was so fine and was very difficult to handle. A majority of the tests were conducted using the 0.076 mm diameter (302 stainless). It proved to be less brittle than the tungsten and provided adequate heating and strength characteristics.

Coating Material and Procedure

A number of different liquids were initially used to coat the smoke-wire to produce the smoke filaments. These included several types of lubricating and mineral oils and a commercially available product, Life-Like Model Train Smoke, produced by Life-Like Products, Baltimore, Md. The results were similar to those achieved in Ref. 11, which indicated that the model train smoke produced the best smoke filaments. This product is composed of a commercial grade mineral oil to which a small amount of oil of anise and blue dye have been added.[13] There would be obvious safety problems associated with large quantities of the smoke, but since there are such small amounts produced and in this application the open circuit tunnel exits to the outside of the laboratory, there were no safety problems. Reference 7 even indicates that since the amount of smoke is so small the method is quite suitable for limited use in closed circuit tunnels.

There appear to be a number of methods which can be used to coat the wire, each with its own advantage and disadvantage. Reference 7 documents a pressurized gravity feed method which might be suitable for a vertical wire such as B-B in Fig. 1. A method similar to this was tried but there were problems with the large droplets running down the wire and coating the surface. These droplets periodically would be blown off the wire and would wet the surface of the airfoil model. Nagib[8] has developed a "windshield wiper" device which automatically coats the wire by wiping oil along the wire, but this apparatus would have to be located within the test section which was unsuitable for the type of test to be conducted.

The best technique for this application was a manual coating. The rear wall of the test section was fitted with an easily removable section. Between each use of the wire the section was removed and the wire carefully wiped with a cotton-tipped applicator soaked with oil. This provided a uniform coating with no model fouling.

Photographic Technique and Lighting

Different lighting and photographic procedures were used for each of the two wire orientations (Fig. 1). In both cases, still and high-speed movie photography were used. The still photographs were taken using a Graflex Graphic View camera with an ACU-Tessar 210 (f:6.3) lens using Polaroid Type 57 and Kodak Royal-X Pan films. The high speed motion pictures were taken using either a Wollensak WF-3 Fastax camera (1000-3000 frames/s) or a DBM-5 Milliken camera (128-250 frames/s). Both cameras used Kodak 4-X negative, 16 mm, 7224 film.

For the planform views of the model, the horizontal wire position (A-A) was used and the cameras were mounted below the glass floor section of the model. The camera was positioned normal to the chord of the airfoil for each angle of attack studied. Lighting for the still photographs was accomplished using two high intensity General Radio Type 1532 strobolumes having a 20 μs flash duration and triggered by the camera shutter. For the planform views, the lights were directed along the span of the airfoil, as shown in Fig. 3. To help reduce the light intensity falloff across the span of the wing, a mirror was placed on the back of the tunnel; this helped provide uniform illumination across the span.

For the vertical wire position, the camera was aimed along the spanwise axis of the wing. The model was illuminated from above and below the wing, normal to the wing, through 25.0 mm slits in the top and bottom of the test section.

For the Fastax camera, continuous lighting was supplied by a single 1000 W quartz lamp. The Milliken camera was synchronized with two GENRAD Type 1540 strobolumes triggered by the camera.

Each of the methods mentioned provided adequate illumination and contrast for photographing the smoke streaklines. Results obtained using these methods will be shown later in the paper.

Experimental Procedure and Timing Circuit

As the coated wire is heated, fine smoke streaklines are formed at each droplet on the wire ($\simeq 8$ lines per cm for the 0.076 mm wire). Depending upon the voltage across the wire, the beads can be vaporized very rapidly or, if a lower voltage is used, continuous filaments of adequate density will emanate from the wire for as long as 2 s. With even lower current, the streaklines become fainter and cannot be photographed. For the 0.076 mm diam 302 stainless wire of 0.40 m length, the wire was heated using a power supply setting of approximately 50 V. Both ac and dc power supplies were used. One interesting aspect of using the ac power supply is that as the wire is heated and cooled due to the alternating voltage, the smoke density varies in a similar manner and time streaklines can be formed.

Because of the relatively short duration of the smoke generation for a single wire coating, it is important that the event being photographed, the lighting, the camera and the smoke be properly controlled and synchronized. To accomplish this, a timing circuit was designed. The design is a modification of that shown in Ref. 7 and is included here in Fig. 4.

The use of the timing/control circuit reduces the photographing of a given event to a single step operation. The circuit applies power to the smoke-wire and, with the appropriate user set delay, it will activate a camera and lights using a solenoid attached to a camera trigger. The solenoid trigger and camera are set, the wire is oiled, and the start button is momentarily depressed. This causes the smoke to be generated and the camera triggered when the smoke has reached the desired intensity and location. Two variable potentiometers control the timing circuits in the controller. The first controls the length of time the current passes through the wire and the second controls the time delay before the camera is triggered. A similar circuit could be designed so that the photograph could be triggered by some event within the tunnel such as an oscillating flap or airfoil. This would allow for a conditional photographic sampling. The timing circuit is invaluable in the practical application of the smoke-wire technique.

Application of the Smoke-Wire Technique

The initial test results were for the smoke-wire alone. These tests were conducted to evaluate the wire wake influence on the stability of the smoke streaklines generated at the wire. Both photographic and hot-wire data were collected for the wire alone cases. So long as the Re_d for the wire remained below 20 (as in all cases presented), there was no apparent breakdown in the smoke streaklines for the entire length of

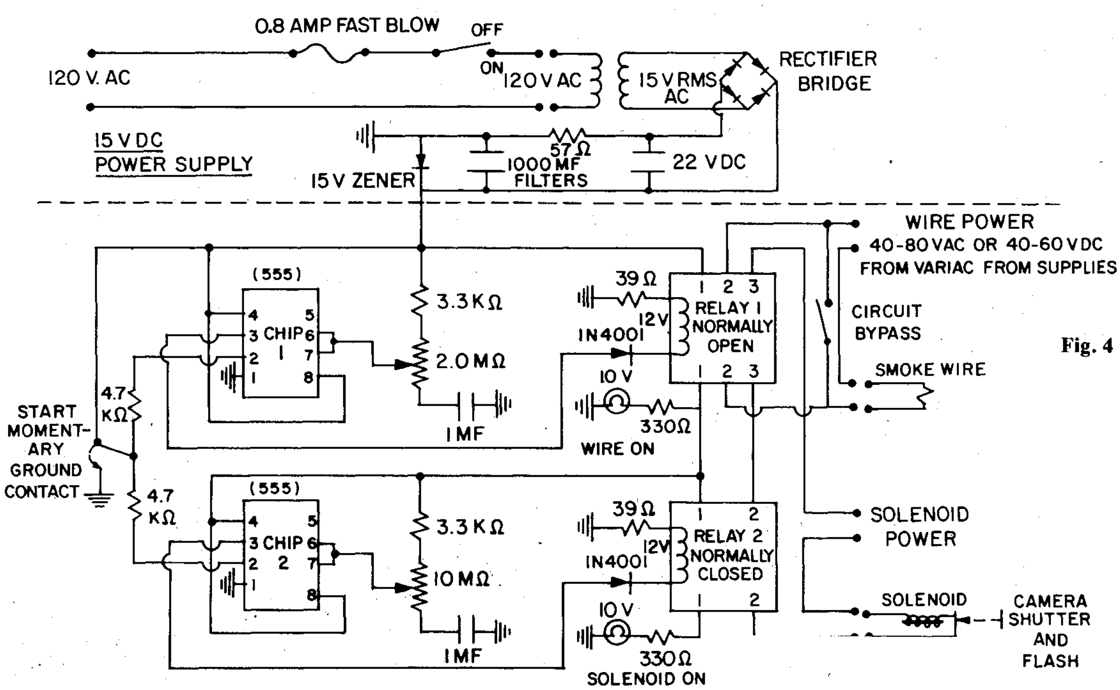

Fig. 4 Timing circuit diagram.

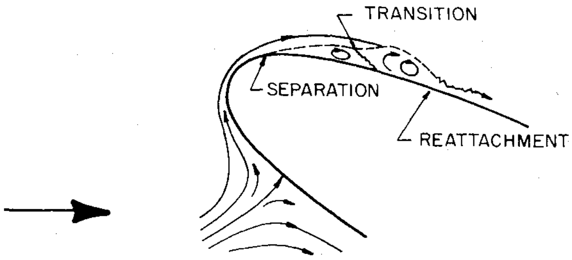

Fig. 5 Schematic of leading edge separation bubble.

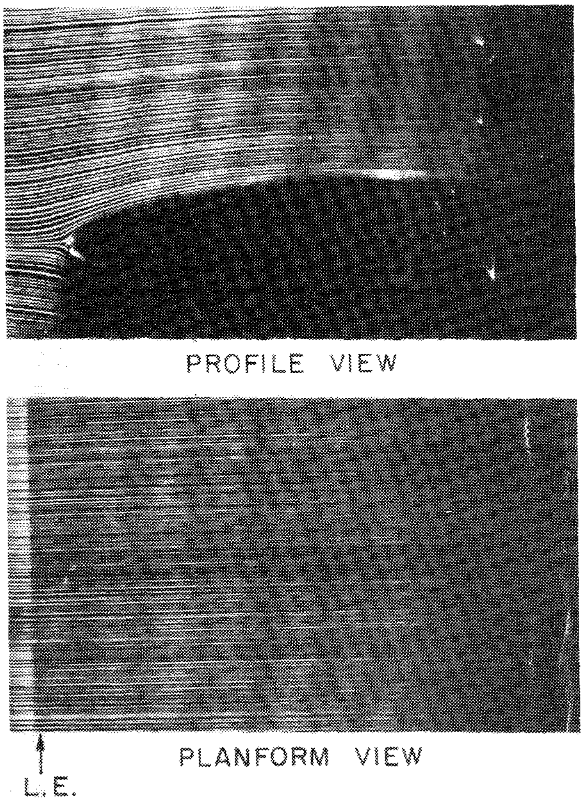

Fig. 6 Smoke-wire visualization for $\alpha = 0$ deg and $Re_c = 55{,}000$.

the test section (1.5 m). Hot-wire traverses of the wire wake indicated a slight momentum deficit in the region 100 mm downstream of the wire but no increase in turbulence levels nor any periodic disturbances created by the wire.

The remainder of the tests were conducted to help in the study of the low Reynolds number characteristics of the NACA 66_3-018 airfoil section and, in particular, details of the leading edge separation bubble.

The leading edge separation bubble, shown in Fig. 5, is formed when the laminar boundary layer separates from the surface as a result of the strong adverse pressure gradient downstream of the point of minimum pressure. This separated shear layer is very unstable and transition usually begins a short distance downstream of separation, as a result of the amplification of velocity disturbances present immediately after separation. Reattachment can occur while the shear layer is undergoing transition or after the transition process is complete and the flow is turbulent. The region between separation and reattachment is referred to as the separation bubble. The fluid in the laminar portion of the bubble moves very slowly, while the fluid in the transitional or turbulent portion moves vigorously in a recirculating pattern. Those factors which affect boundary layer separation also affect the separation bubble and transition in the separated shear layer, namely: thickness of the boundary layer at separation, angle of attack, freestream turbulence level

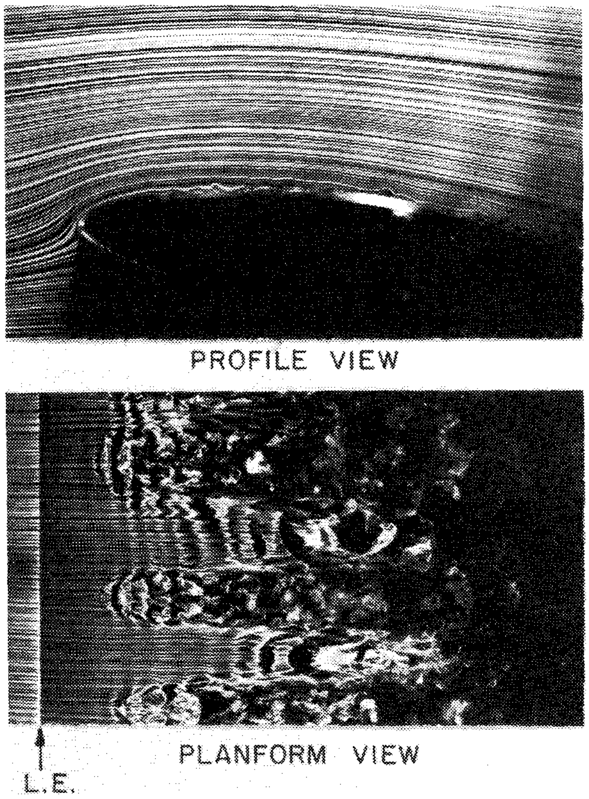

Fig. 7 Smoke-wire visualization for $\alpha = 8$ deg and $Re_c = 55{,}000$.

and/or other free stream disturbances and surface roughness. The transition process in the separated shear layer is the keystone which determines the size and shape of the bubble, as well as how rapidly the developing turbulent boundary-layer grows over the remaining portion of the airfoil.

It is generally agreed that transition from laminar to turbulent flow may be described as a series of events which take place more or less continuously, depending on the flow problem studied. Since turbulence is essentially a three-dimensional phenomenon, the breakdown of a two-dimensional laminar flow may be viewed as the process whereby finite amplitude velocity fluctuations, or traveling wave disturbances, acquire significant three-dimensionality.[14] Transition has been graphically described as the process by which the straight and parallel vortex lines of a two-dimensional laminar flow deform into a constantly changing and twisting three-dimensional mess called "turbulence."[15]

Figures 6-10 show a series of planform and profile views of the airfoil section for a range of angles of attack from 0 to 15 deg for a Reynolds number based on chord length, $Re_c = 55{,}000$. In the planform views, the wire height was carefully adjusted so that the sheet of smoke impinged on the leading edge at the stagnation point. At $\alpha = 0$ deg, a trailing edge separation is noted at about 85% chord and the flow is everywhere laminar. At $\alpha = 10$ and 12 deg, the separation bubble is quite apparent in the profile view. The planform view is a very graphic illustration of the breakdown of the laminar flow through transition in the free shear layer and the subsequent turbulent reattachment. This series of photographs was taken using ac current to the wire, and the variations in smoke density are particularly evident in the profile views. The spanwise uniformity of the overall transition process is evident. A close-up view of the breakdown shown in Fig. 11 illustrates that the transition process in the free shear layer is indeed three-dimensional. Figure 11 shows two successive frames of the high speed motion picture film at 3000 fps, again at a $Re_c = 55{,}000$.

Note: In subsequent smoke photographs, the flow is from left to right, with the smoke-wire to the left-hand side of the

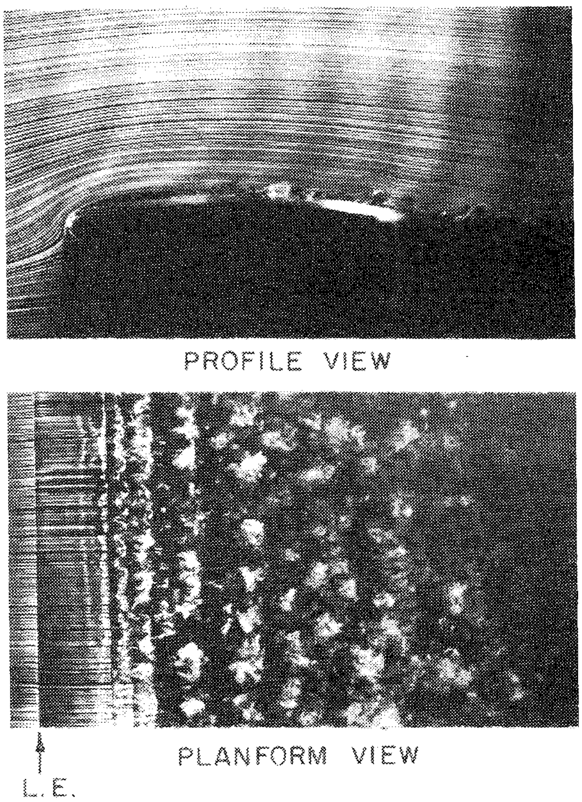

Fig. 8 Smoke-wire visualization for $\alpha = 10$ deg and $Re_c = 55{,}000$.

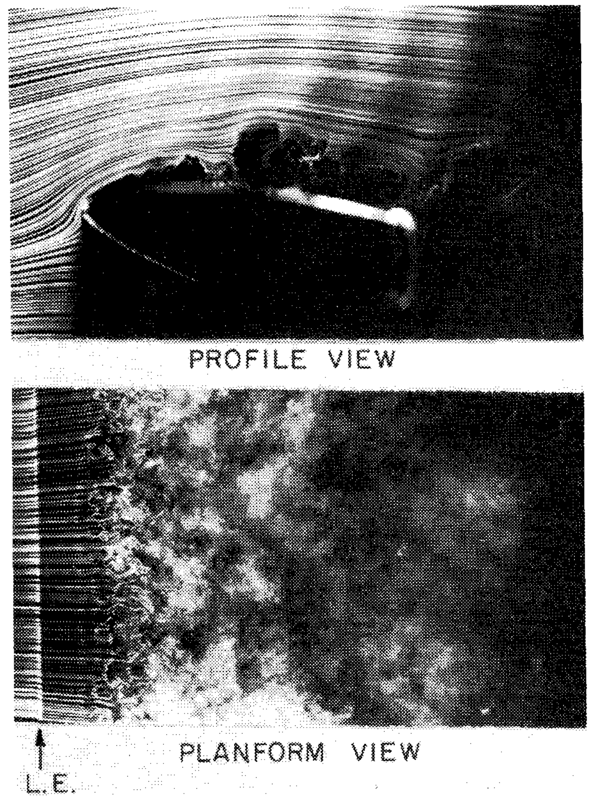

Fig. 10 Smoke-wire visualization for $\alpha = 15$ deg and $Re_c = 55{,}000$.

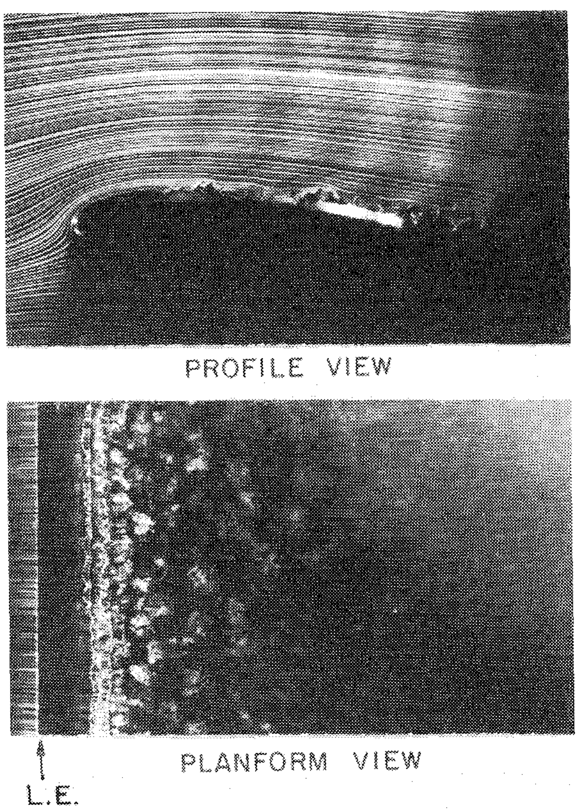

Fig. 9 Smoke-wire visualization for $\alpha = 12$ deg and $Re_c = 55{,}000$.

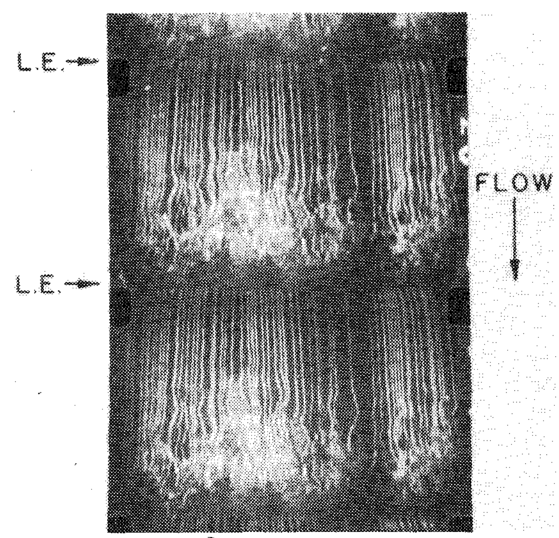

Fig. 11 High speed motion picture (close up) for $\alpha = 12$ deg and $Re_c = 55{,}000$.

photographs. In some photographs the airfoil leading edge will be indicated with the symbol, L. E.

Figure 7 shows some of the more interesting results which have been observed. At $\alpha = 8$ deg, the bubble has not formed uniformly across the span of the wing and transition is highly erratic and three-dimensional. This has helped to explain some of the unusual airfoil characteristics at these low Reynolds numbers.[16,17]

A number of other studies have been conducted which indicate the utility and flexibility of the smoke-wire technique in the investigation of the separation and transition phenomena.[16,17] These experiments include the introduction of higher freestream turbulence levels through grid turbulence, and the study of the development of the turbulent boundary layer by moving the sheet of smoke streaklines relative to the airfoil.

An examination of the smoke photographs substantiates the notions of a highly unstable two-dimensional flow which breaks down in a very definite manner to a three-dimensional chaotic turbulent flow. These smoke photographs represent visual descriptions of separated shear layer transition.

Although this visual technique has only been applied for chord Reynolds numbers less than 120,000, the basic transition process should follow the same series of events at higher Reynolds numbers. For example, using the same airfoil, the beginning of the transition process moves toward the separation location as the freestream velocity is increased. The length of the transition region also decreases with higher freestream velocities. Thus, the understanding gained at low Reynolds numbers can definitely help develop a physical model of transition which will be useful at high Reynolds numbers.

Summary

The paper has presented and discussed the smoke-wire flow visualization technique. This included a description of the technique and associated equipment, and a study of the influence of the wire on the undisturbed flowfield. The specific application of the technique, which was presented, was the study of the transition of the free shear layer associated with the laminar separation bubble on a low Reynolds number, NACA 66_3-018 airfoil section. The paper demonstrated that the smoke-wire technique provided the capability of introducing the smoke streaklines into a flowfield and, thus, provided a valuable visualization capability for the complex flow phenomena studied.

Acknowledgments

This research was sponsored by NASA Langley Research Center under Grant NSG-1419. The authors would like to thank Dr. H. Nagib of the Illinois Institute of Technology for his help during the initial phases of this project. The efforts of Mr. Bernard Jansen Jr. in the design and fabrication of the control/timer and assistance in collecting the photographic data are also acknowledged.

References

[1]Mach, L., "Uber die Sichtbarmachung von Luftstromlinien," *Zeitschrift für Luftschiffahrt und Physik der Atmosphare,* Vol. 15, Heft 6, 1896, pp. 129-139.

[2]Mueller, T. J., "Smoke Visualization of Subsonic and Supersonic Flows (The Legacy of F. N. M. Brown)," University of Notre Dame Report UNDAS TN-3412-1, June 1978.

[3]Cornish, J. J., "A Device for the Direct Measurements of Unsteady Air Flows and Some Characteristics of Boundary Layer Transition," Mississippi State University, Aerophysics Research Note 24, 1964, p. 1.

[4]Sanders, C. J., and Thompson, J. F., "An Evaluation of the Smoke-Wire Technique of Measuring Velocities in Air," Mississippi State University, Aerophysics Research Rept. 70, Oct. 1966.

[5]Yamada, H., "Instantaneous Measurements of Air Flows by Smoke-Wire Technique," *Transactions of Japan Mechanical Engineers,* Vol. 39, 1973, p. 726.

[6]Cornish, J. J., private communication, Sept. 1979.

[7]Corke, T., Koga, D., Drubka, R., and Nagib, H., "A New Technique for Introducing Controlled Sheets of Smoke Streaklines in Wind Tunnels," *Proceedings of International Congress on Instrumentation in Aerospace Simulation Facilities,* IEEE Publ. 77 CH 1251-8 AES, 1974, p. 74.

[8]Nagib, H. M., "Visualization of Turbulent and Complex Flows Using Controlled Sheets of Smoke Streaklines," *Proceedings of the International Symposium on Flow Visualization,* Tokyo, Oct. 1977, pp. 181-186 (also supplement 29-1 to 29-7).

[9]Kasagi, N., Hirata, M., and Yokobori, S., "Visual Studies of Large Eddy Structures in Turbulent Shear Flows by Means of Smoke-Wire Method," *Proceedings of the International Symposium on Flow Visualization,* Tokyo, Oct. 1977, pp. 169-174.

[10]Torii, T., "Flow Visualization by Smoke-Wire Technique," *Proceedings of the International Symposium on Flow Visualization,* Tokyo, Oct. 1977, pp. 175-180.

[11]Cornell, D., "Smoke Generation for Flow Visualization," Mississippi State University, Aerophysics Research Rept. 54, Nov. 1964.

[12]Blevins, R. D., *Flow Induced Vibration,* Van Nostrand Reinhold Co., 1977.

[13]Lipnick, D., private communication, Life-Like Products, Baltimore, Md., Nov. 1979.

[14]Cebeci, T., and Bradshaw, P., *Momentum Transfer in Boundary Layer,* Hemisphere Publishing Corp., 1977.

[15]Betchov, R., "Transition," *Handbook of Turbulence,* Vol. 1, edited by W. Frost and T. H. Moulden, Plenum Publishing Co., 1977, pp. 147-164.

[16]Batill, S. M. and Mueller, T. J., "Visualization of the Laminar-Turbulent Transition in the Flow over an Airfoil Using the Smoke-Wire Technique," AIAA Paper 80-0421, presented at the AIAA 11th Aerodynamic Testing Conference, Colorado Springs, Colo., March 1980.

[17]Mueller, T. J. and Batill, S. M., "Experimental Studies of the Laminar Separation Bubble on a Two-Dimensional Airfoil at Low Reynolds Numbers," AIAA Paper 80-1440, presented at the AIAA 13th Fluid and Plasma Dynamics Conference, Snowmass, Colo., July 1980.