

NASA Contractor Report 4003

NASA-CR-4003 19860018905

Feasibility of Generating an "Artificial" Burst in a Turbulent Boundary Layer

Mohamed Gad-el-Hak

CONTRACT NAS1-17951
JULY 1986

LIBRARY COPY

JUL 1986
LANGLEY RESEARCH CENTER
LIBRARY, NASA
HAMPTON, VIRGINIA

FOR REFERENCE

NOT TO BE TAKEN FROM THIS ROOM



NASA Contractor Report 4003

Feasibility of Generating
an “Artificial” Burst in
a Turbulent Boundary Layer

Mohamed Gad-el-Hak

Flow Industries, Inc.

Kent, Washington

Prepared for
Langley Research Center
under Contract NAS1-17951

NASA
National Aeronautics
and Space Administration
**Scientific and Technical
Information Branch**

1986

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

PHASE I SBIR - FINAL REPORT

PROJECT SUMMARY

PROJECT TITLE : Feasibility of Generating an "Artificial" Burst
in a Turbulent Boundary Layer

CONTRACT NUMBER : NAS1-17951

ISSUED BY : NASA-Langley Research Center

TECHNICAL MONITORS : J. B. Anders & D. M. Bushnell

CONTRACTOR : Flow Industries, Inc.

PRINCIPAL INVESTIGATOR : Mohamed Gad-el-Hak

DURATION : 13 December 1984 - 24 June 1985

It is generally agreed that the bursting phenomenon is the most significant dynamic event in a turbulent boundary layer. About 80 percent of the momentum transport occurs during these bursts. Previous attempts to understand the physics and structure of these events were frustrated by the fact that bursts occur randomly in space and time and that successive bursts are not necessarily identical. During Phase I of this investigation, "artificial" bursts were generated in laminar and turbulent boundary layers. The burst-like events were produced by withdrawing near-wall fluid from two minute holes separated in the spanwise direction or by pitching a miniature delta wing that was flush-mounted to the wall. Either of these actions generated streamwise vorticity and a low-speed streak that resembled a naturally occurring one. The resulting sequence of events occurred at a given location and at controlled times, allowing detailed examination and comparison with natural, random bursts by means of flow visualization and fast-response probe measurement techniques.

By all available measures, the Phase I research should be considered highly successful. We have generated an artificial burst in a turbulent boundary layer. This will allow detailed study of the dynamics of a bursting event and make it easier to develop methods to control or eliminate bursts, thus reducing drag. We are currently contemplating a novel method to achieve substantial drag reduction. The device combines the beneficial effects of suction and a longitudinally ribbed surface, and will be optimized using artificially-generated bursts. A successful application of the proposed innovation on commercial aircraft will result in an annual fuel savings of several billion dollars.

Table of Contents

	<u>Page</u>
Project Summary	1
Table of Contents	2
1. Introduction	3
2. Experimental Approach	8
2.1 Towing Tank	8
2.2 Flat Plate	8
2.3 Excitation Techniques	8
2.4 Visualization Methods	11
2.5 Velocity Measurements	13
2.6 Pattern Recognition Algorithms	13
3. Bursts in Laminar Flow	15
4. Bursts in a Turbulent Boundary Layer	25
5. Pattern Recognition of Bursts and Streaks	32
6. Summary	34
References	36
Appendix I: Pattern Recognition Algorithms	39

1. Introduction

Recent turbulent boundary layer research has clearly shown that the wall region is dominated by a sequence of eddy motions that are collectively called the bursting phenomenon. This process was reviewed by Willmarth (1975) and summarized by Blackwelder (1978). Qualitatively, the process begins with a pair of elongated, streamwise, counter-rotating vortices having diameters of approximately $40 \nu/u_\tau$, where ν/u_τ is the viscous scale, ν is the kinematic viscosity and u_τ is the friction velocity. The vortices exist in a strong shear and induce low- and high-speed regions between them as shown in Section BB of Figure 1. The vortices and the accompanying eddy structures occur randomly in space and time. However, their appearance is regular enough that an average spanwise wavelength of approximately 80 to 100 ν/u_τ has been identified by Kline et al. (1967) and others. Kline et al. also observed that the low-speed regions grow downstream and develop inflectional $U(y)$ profiles, as sketched in Figure 1. At approximately the same time, the interface between the low- and high-speed fluid begins to oscillate. The low-speed region lifts up away from the wall as the oscillation amplitude increases, and then the flow rapidly breaks down into a completely random pattern. Since this latter process occurs on a very short time scale, Kline et al. called it a "burst." Corino & Brodkey (1969) showed that the low-speed regions are quite narrow, i.e., $20 \nu/u_\tau$, and may also have significant shear in the spanwise direction.

Considerably more has been learned about the bursting process during the last decade. For example, Falco (1980) has shown that the wall region is continuously bombarded by "pockets" of high-speed fluid originating in the logarithmic and possibly the outer layers of the flow. These pockets tend to promote and/or enhance the inflectional velocity profiles by increasing the instantaneous shear leading to a more rapidly growing instability. Blackwelder & Haritonidis (1983) have shown that the frequency of occurrence of these events scales with the viscous parameters consistent with the usual boundary layer scaling arguments.

The complexity of the bursting phenomenon should be apparent from the fact that extensive investigations have failed to provide an explanation for the origin of bursting (Offen & Kline, 1975; Praturi & Brodkey, 1978; Falco, 1979; 1980; Smith, 1983) or the topological characteristics of the bursting coherent

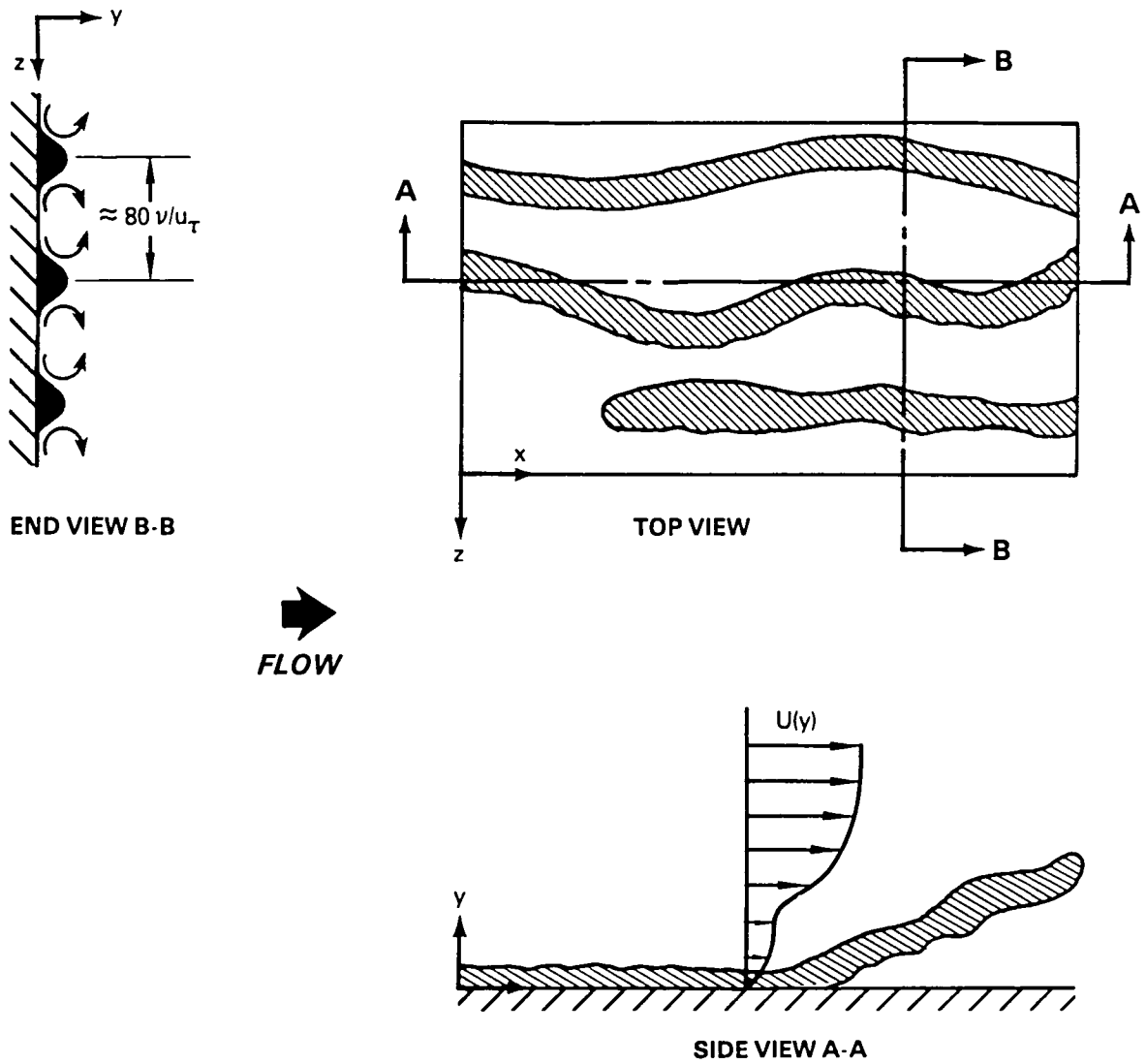


Figure 1. Sketch of the Low-Speed Streaks in the Wall Region. The Counter Rotating Eddies between the Streaks are Indicated in Section B-B.

structure, as well as its evolution and dynamics (Hussain, 1983a). Sophisticated experiments have been conducted to capture the bursting signature (Blackwelder & Kaplan, 1976; Nishioka et al., 1981; Antonia, 1981), but it is clear that the educed signature is dependent on the detection scheme as well as on the threshold level of a given detection scheme (Kunen et al., 1983; Sato, 1983).

Hussain (1983b) reiterated that a single-point detection of an inherently three-dimensional random structure must produce significant smearing. That is, eduction of the bursting coherent structure should not only involve a three-dimensional detection scheme but also require first the identification of the mode (i.e., spatial configuration) of the structure and then the probability density distribution as a function of the characteristic structure parameters, like shape, size, strength, orientation, convection velocity, etc. Furthermore, a stationary sensor may intersect successive three-dimensional structures (say, hairpin vortices) at different relative spanwise locations, and a structure may advect past a sensor at different transverse displacements so that a stronger structure farther away could not be necessarily differentiated from a weaker structure nearby.

It should thus be clear that an array of probes in a transverse rake must be used for measurement. Furthermore, the measuring rake should be located in between two detection rakes so that the relative spanwise location of the measuring rake within the three-dimensional advecting structure can be determined instantaneously.

Since the coherent vorticity Ω is the principal property of a coherent structure, structure detection must be based on Ω and not on the correlation of velocity, pressure and/or intermittency signals (Hussain 1980). Only large-scale vorticity is involved, however, so a transverse rake of X-wires is adequate to measure the instantaneous map of the spanwise vorticity $\langle \Omega \rangle$ in the (y, t) plane. From the smoothed maps $\langle \Omega(y, t) \rangle$, one should decide which structures should be accepted. That is, eduction involves accepting only those structures of a given mode with the peak value (denoting strength) of $\langle \Omega \rangle$ above a certain level and the peak location at an optimally selected transverse location and accepting structures of a given shape and size. The accepted structures should then be ensemble averaged after proper phase alignment. One way to align is appropriate time shifting of realizations via the method of iterative cross-correlation of each realization with the ensemble average

(Zilberman et al., 1977). Whatever survives the phase averaging (i.e., ensemble averaging at a fixed phase) of the appropriately aligned realizations is the coherent structure, and the departure of each realization from the phase averaging is the corresponding incoherent turbulence. The phase-averaged contours of coherent vorticity, coherent and incoherent Reynolds stress, coherent production, etc., provide the necessary structure properties. The phase-averaged velocity vector pattern in the frame of the structure superimposed on the contours of $\langle \Omega \rangle$ will denote the spatial variations of entrainment (Hussain & Zaman, 1980).

It is necessary to emphasize that these elaborate efforts are justified if the flow is characterized by "preferred modes", as the coherent structure approach to turbulence is not very helpful if the flow has a large variety of coherent structures. Furthermore, capturing an individual structure via spatial smoothing is not helpful, as there is no test for convergence of the smoothing that removes sharp fronts otherwise retained by ensemble averaging. Also, one must assure that the educed structure is not "freak" and does indeed represent a "preferred mode". A classical example of such a freak structure is the single, large horseshoe vortex detected by Wygnanski et al. (1976) and Cantwell et al. (1978) by ensemble averaging an artificial turbulent spot. The results of Gad-el-Hak et al. (1981) clearly indicate the dynamic insignificance of such a structure.

Returning to the bursting coherent structure, it should be clear that the variations in their characteristic parameters as well as the random occurrence in time and the random transverse and spanwise displacements of natural bursting structures must have produced unacceptable smearing, thus frustrating prior eduction schemes in the boundary layer. Furthermore, we are unaware of any attempt to determine if all structures included in the educed bursting signature (which differed from a phase average) are of the same mode. In an attempt to remove significantly the inherent smearing in the eduction of natural bursting structures, a new approach has been attempted: eduction of artificially induced bursting. The structure details can then be educed via measurements phase-locked to the excitation (Hussain & Reynolds, 1972), much the same as was done in the case of the artificial turbulent spot (Gad-el-Hak et al., 1981). During the first phase of this work, we were able to generate an artificial burst in both laminar and turbulent boundary layers. The sequence of events induced artificially was compared to that of a natural

burst in a turbulent boundary layer using flow visualization and hot-film probe measurements. In all the comparisons that we have made thus far, the artificial event was kinematically and dynamically identical to the bursts occurring randomly in space and time in a turbulent boundary layer.

2. Experimental Approach

2.1 Towing Tank

Turbulent and laminar boundary layers were generated by towing a flat plate in a water channel that is 18 meters long, 1.2 meters wide and 0.9 meter deep. The towing tank, shown in Figure 2, has been described by Gad-el-Hak et al. (1981). The flat plate was rigidly mounted under a carriage that rides on two tracks mounted on top of the tank. During towing, the carriage was supported by an oil film to ensure a vibrationless tow, having an equivalent freestream turbulence of about 0.1 percent. The carriage was towed by two cables driven through a reduction gear by a 1.5-hp Boston Ratiotrol motor. The towing speed was regulated within an accuracy of 0.1 percent. The system was able to achieve towing speeds between 5 and 140 cm/sec for the present study. However, most of the runs reported here were conducted at a speed of 20 cm/sec.

2.2 Flat Plate

A unique, zero-pressure-gradient flat plate was constructed for the present investigation. The 1-meter by 2-meter structure, shown in Figure 3, is made of glass-reinforced polycarbonate plate 6 mm thick, glued to a stainless steel frame designed for minimum obstruction to the flow. The plate has an elliptic nose at the leading edge and an adjustable lifting flap at the trailing edge. To avoid leading-edge separation and premature transition, the flap is adjusted so that the stagnation line near the leading edge is located on the working surface of the plate. The plate's smooth surface and flatness to within a few microns make it one of the most controlled test beds available for boundary layer research. A laminar boundary layer can be obtained over the entire working surface for towing speeds in the range of 5 to 80 cm/sec. Trips are used to generate a fully developed turbulent boundary layer. The trips are brass cylinders 0.32 cm in diameter and 0.25 cm high placed 5 cm downstream of the leading edge and having their axes perpendicular to the flat plate.

2.3 Excitation Techniques

To generate an artificial burst, several excitation techniques were tried. Suction was applied suddenly through one, two, three or four holes separated in the spanwise direction by a distance of $\Delta z^+ = 100$. The minute holes were 0.4 mm in diameter and were connected to a vacuum chamber controlled with a solenoid valve that is driven by a signal generator. This allowed the sudden

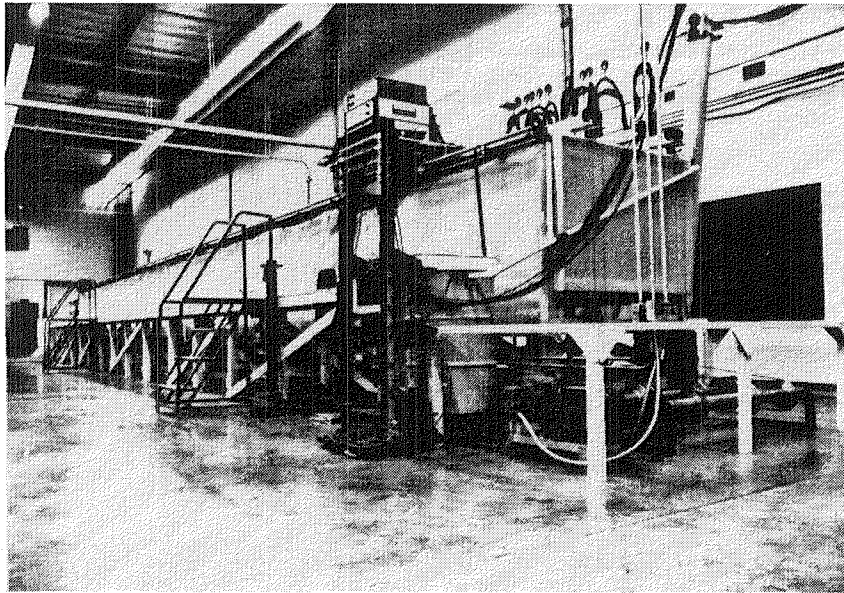


Figure 2. Flow Industries' 18-Meter Towing Tank

FLOW →

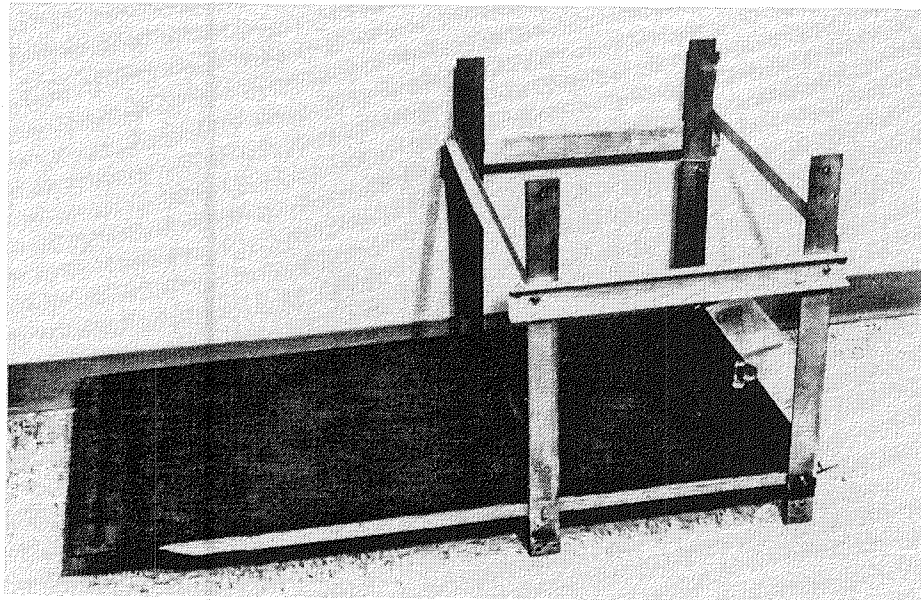


Figure 3. Photograph of the Zero-Pressure-Gradient Flat Plate

withdrawal of a given amount of fluid and the generation of a horseshoe vortex that evolved into a burst.

The second excitation technique tried was the sudden pitching of a miniature delta wing having a span of 80 wall units. The wing, with its apex facing the flow, was normally flush-mounted to the surface of the plate. At the desired instant, a pin centered around the trailing edge of the wing was driven upward using a solenoid to pitch the delta wing to a negative angle of attack of 30° . This produced two strong, longitudinal, counter-rotating vortices that lifted away from the wall and evolved into a burst. The burst generators were located 79 cm downstream of the plate's leading edge. Figure 4 is a close-up photograph of the surface of the flat plate, showing the flush-mounted delta wing and the four suction holes (located to the left of the white marks in the picture).

2.4 Visualization Methods

To visualize the bursting events in laminar and turbulent boundary layers, both fluorescent dye and hydrogen-bubble techniques were used. The dyes were seeped into the boundary layer through a spanwise slot 0.15 mm wide and 15 cm long and located 77 cm downstream of the leading edge of the flat plate. The slot is shown in the photograph in Figure 4 just upstream of the burst generators. The dye slot was milled at a 45° angle inclined toward the plate's trailing edge to minimize the flow disturbance. The hydrogen bubbles were generated using a stainless steel wire having a diameter of 50 microns and a length of 10 cm. The wire was placed at different locations either parallel to or perpendicular to the flat plate to obtain top views or side views, respectively, of the flow field. To create time lines, a standard circuit was employed to supply intermittently 100 volts to the wire, which acted as a cathode.

Both the fluorescent dyes and the hydrogen bubbles were illuminated using a sheet of laser light projected in the desired plane. This provided an extra degree of freedom in observing the bursting events, because both the tracer and the light location could be controlled within the limitations of the experimental apparatus. In order to generate a sheet of light, a 5-watt argon-ion laser (Spectra Physics Model 164) was used with a mirror mounted on an optical scanner having a natural frequency of 720 Hz (General Scanning Inc.) and driven by a sine-wave signal generator of the desired frequency. The frequency of the

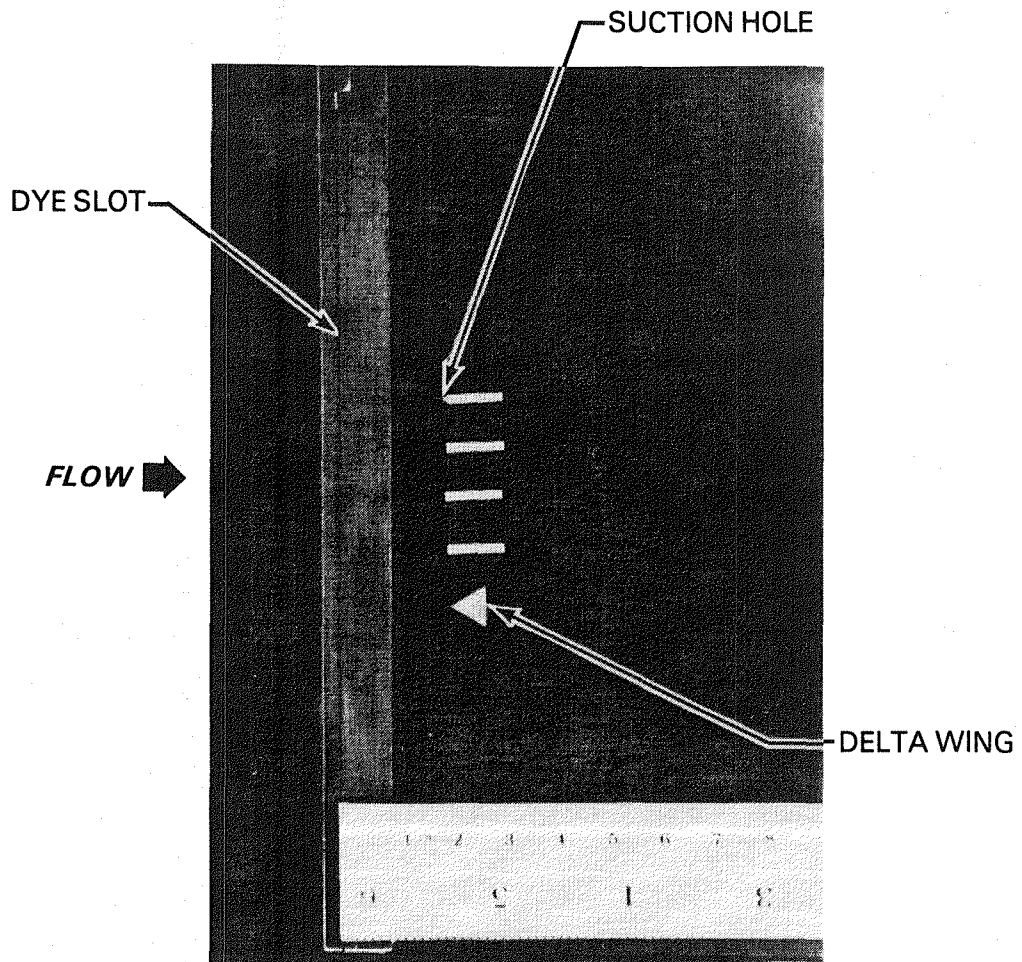


Figure 4. Close Up of the Flush-Mounted Delta Wing and the Suction Holes

sine wave was usually set equal to the inverse of the shutter speed of the camera. The light sheets were approximately 1 mm thick, which was sufficient to resolve the large structure within the turbulent regions. A vertical sheet of laser light parallel to the flow was used to visualize side views of the bursting event, and a horizontal sheet near the surface of the plate was used to obtain top views of the flow field.

2.5 Velocity Measurements

Miniature boundary layer hot-film probes (TSI Model 1260) were used in the present investigation to measure the longitudinal mean and fluctuating velocities. The probe diameters were 0.025 mm, and their sensing lengths were 0.25 mm. A probe traverse powered by a stepping motor and controlled through an APPLE II microcomputer was used for surveying the boundary layers. Conventional statistical quantities, such as the mean and the root mean square, were computed from the velocity signals.

2.6 Pattern Recognition Algorithms

A new pattern recognition technique that utilizes the streamwise velocity signal from three hot-film probes was developed to detect low-speed streaks (Gad-el-Hak et al., 1984). The probes were located at $y^+ = 10$ at the same streamwise position with a spanwise separation of approximately $20 \nu/u_\tau$. Thus, the total array spanned $40 \nu/u_\tau$, which is approximately half the average low-speed streak spacing. A pattern recognition algorithm identified a low-speed region whenever all three signals were less than the local mean velocity by one-half the root-mean-square (rms) value, and the velocity measured by the middle probe was less than the velocity on either side. The beginning and end of each low-speed region could thus be identified, and the streaks' average length and frequency computed.

To test this algorithm, experiments were first carried out using a rake of twelve velocity probes located at $y^+ = 10$ but having a significantly broader spanwise extent. Low-speed streaks were readily identified using the isovelocity contours computed from the rake's output, and their spacing was in reasonable agreement with results obtained from visualization experiments conducted under similar conditions. The results of the algorithm were compared with the low-speed streaks obtained from the rake. The comparison showed that the detected algorithm picked out the streaks exceedingly well, and that the

streaks meander in the spanwise direction so that often a single streak crosses the probes two or more times, resulting in multiple detections.

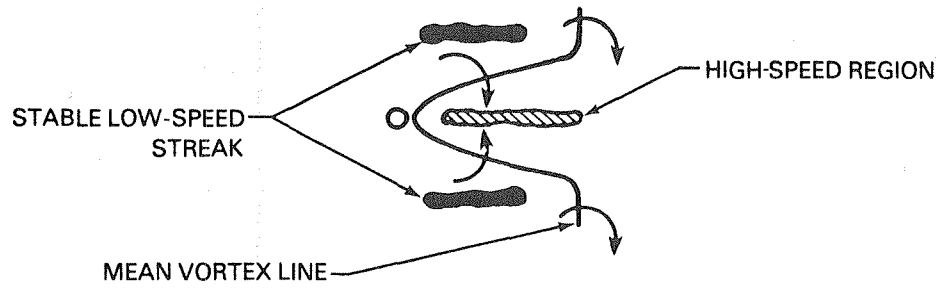
The second pattern-recognition algorithm employed in the present investigation was a burst detection scheme using the variable-interval time-averaging (VITA) technique developed by Blackwelder & Kaplan (1976). A single hot-film probe located at $y^+ = 20$ was used for burst detection. The program counted the number of bursts that occur near the wall and recorded their intensities. The low-speed streak algorithm and the burst detection program are reproduced in Appendix I. The FORTRAN listing also includes a conventional statistics program whose output is used by the burst and streak detectors.

3. Bursts in Laminar Flow

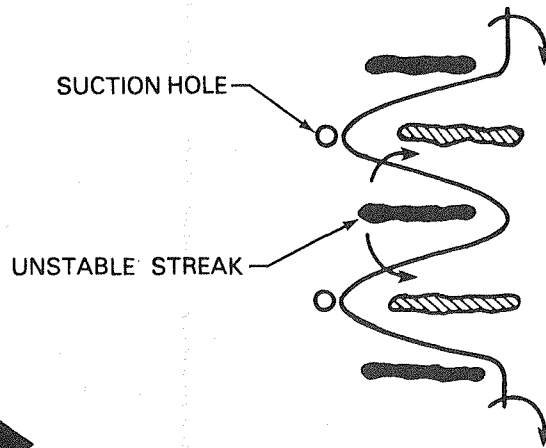
The aim of the present investigation is to generate artificially a bursting event in a turbulent boundary layer. The resulting sequence of events occurs at a given location and at controlled times, thus allowing detailed examination. To understand how the artificial burst generator works, the initial experiments were conducted in a laminar boundary layer environment. This allowed relatively easy visualization of the artificial events, free from the random background that exists in a turbulent boundary layer. Of course, the artificial event evolves differently in the laminar and the turbulent cases. However, the resulting patterns are qualitatively the same.

In a two-dimensional laminar boundary layer, the vorticity vector is in the spanwise direction. Consider the boundary layer to consist of a row of rectilinear vortices aligned in the spanwise direction. Consider further the result of suddenly withdrawing near-wall fluid from one, two or three suction holes separated in the spanwise direction. As shown in the schematic in Figure 5, a near-wall vortex line will then be "pinned down" at the location of the suction holes, thus forming one or more horseshoe-type hoops. In the case of two holes, one horseshoe vortex with its head pointing downstream forms. For three suction holes, two such vortices are generated. The longitudinal vortices exist in a strong shear and induce low- and high-speed regions between them, as shown in Figure 5. For the single-hole case, two low-speed streaks and one high-speed region form. In the case of two holes, three low-speed streaks and two high-speed regions form. Because of the particular direction of rotation of the counter-rotating vortices, only the middle low-speed streak will lift up, causing an unstable, inflectional velocity profile and bursting. Similarly, for three holes, two unstable streaks form, leading to two bursts. These arguments can be extended to an arbitrary number of spanwise suction holes.

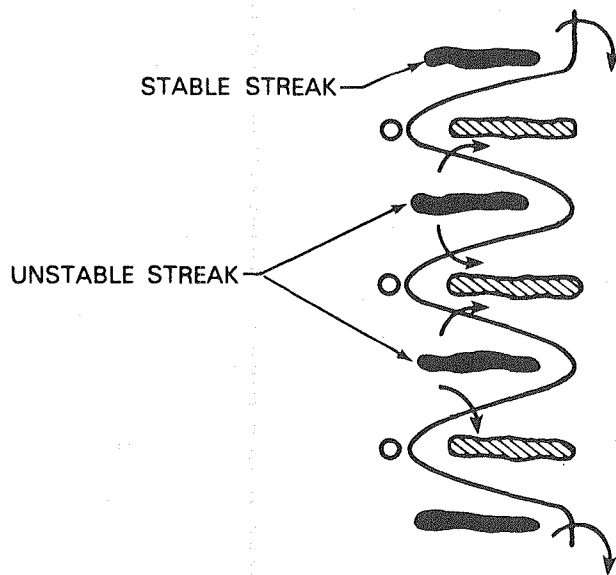
The artificial events resulting from withdrawing near-wall fluid in a laminar boundary layer through one, two, three or four suction holes were visualized using fluorescent dye seeping from the spanwise slot and a horizontal sheet of laser light at the surface of the plate. The results for a freestream speed of 20 cm/sec are shown in individual movie frames in Figures 6, 7, 8 and 9. The flow relative to the flat plate is from left to right, and the time from the onset of suction is indicated on each movie frame. As expected, for a single suction hole, two stable streaks form and no



a. Single Hole



b. Two Holes



c. Three holes

Figure 5. Artificial Burst Generation. Suction Hole Effects on Spanwise Vortex Lines in a Boundary Layer

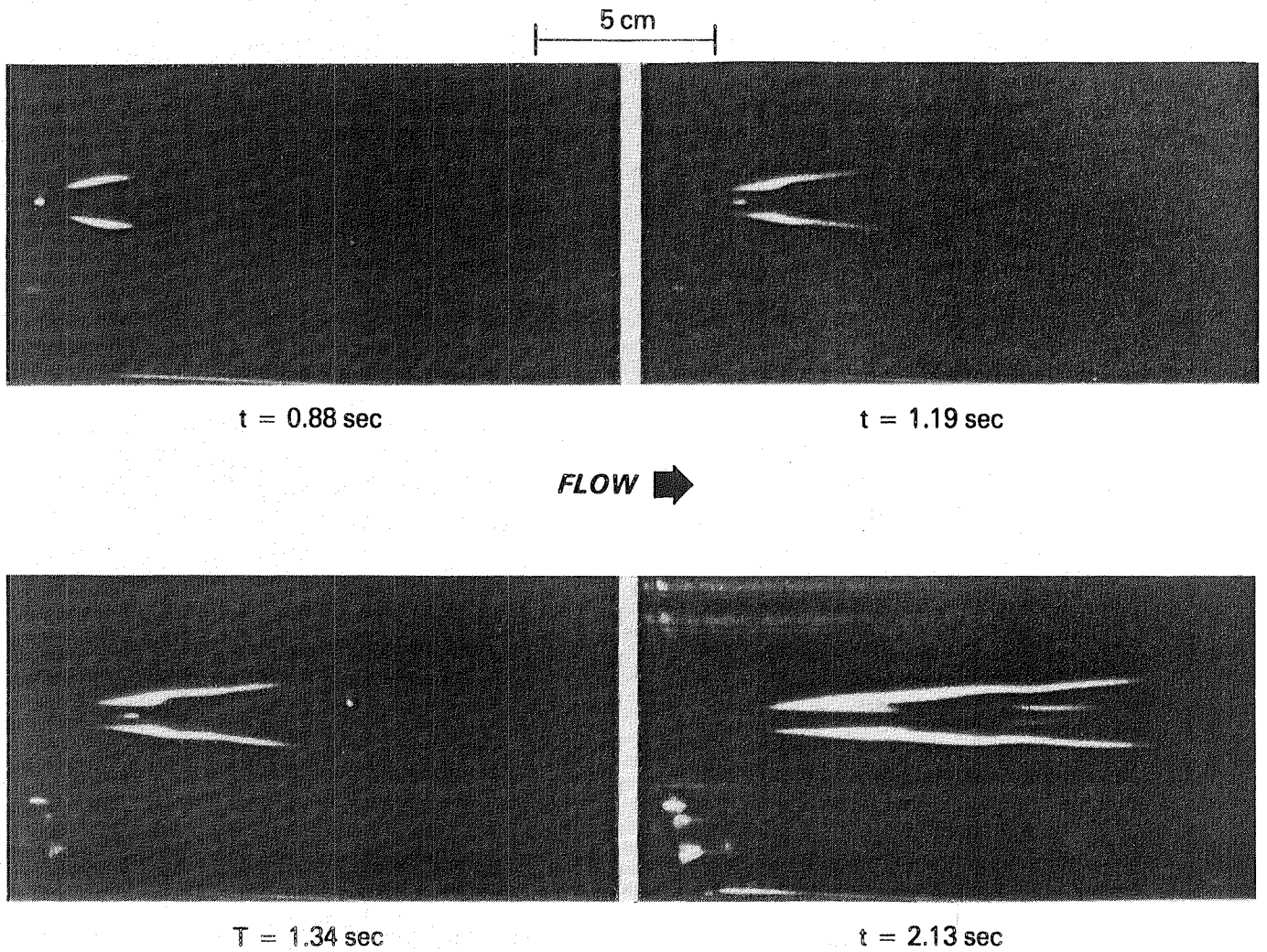


Figure 6. Sequence of Events when Fluid is Withdrawn from a Single Suction Hole. Laminar Boundary Layer is Visualized from the Top Using Fluorescent Dye and Sheet of Laser Light

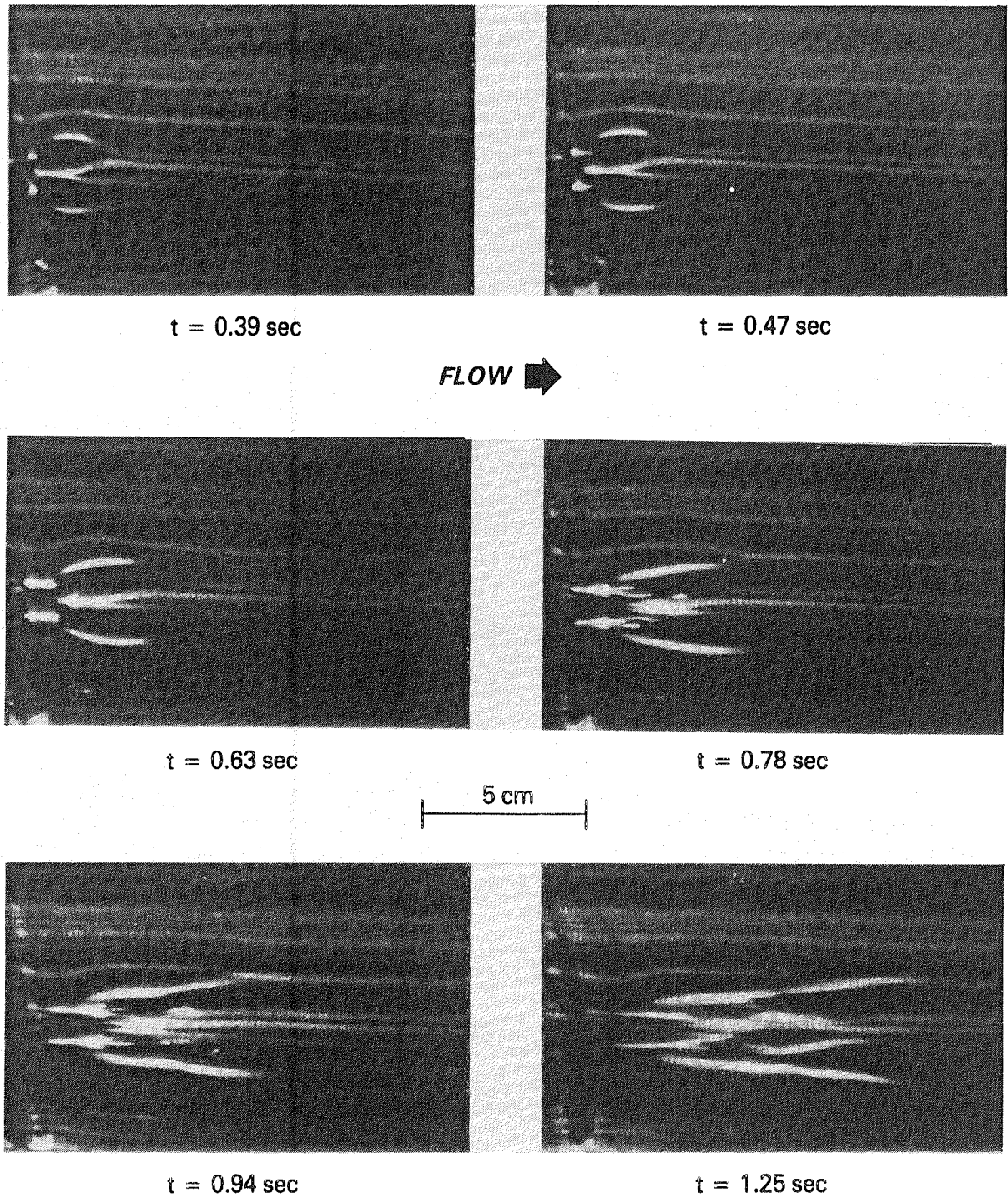


Figure 7. Sequence of Events when Fluid is Withdrawn from Two Holes to Generate a Single Artificial Burst

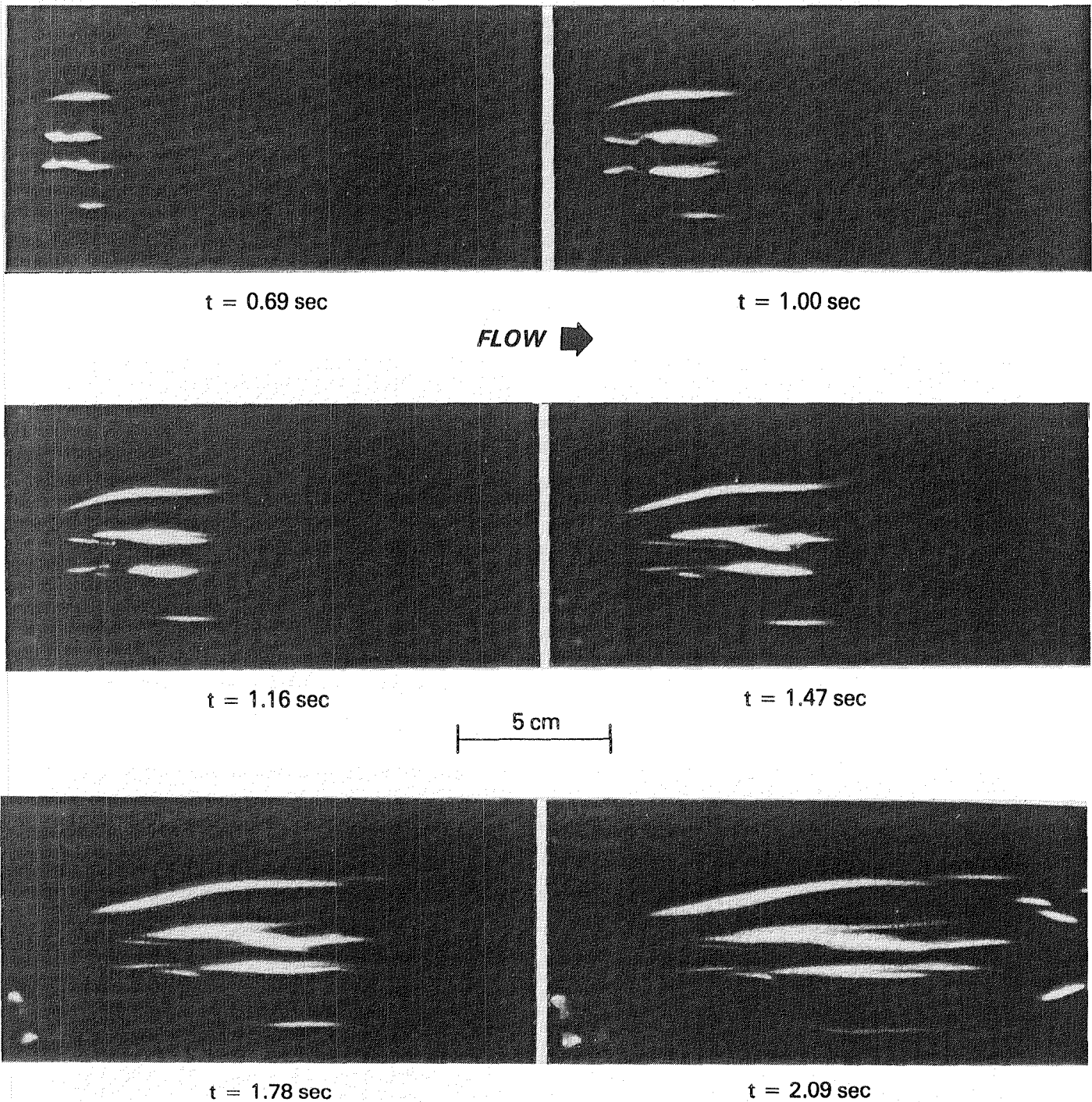


Figure 8. Four Streaks are Generated when Fluid is Withdrawn from Three Suction Holes. Only Two Low-Speed Streaks are Unstable, and Two Bursts are Generated

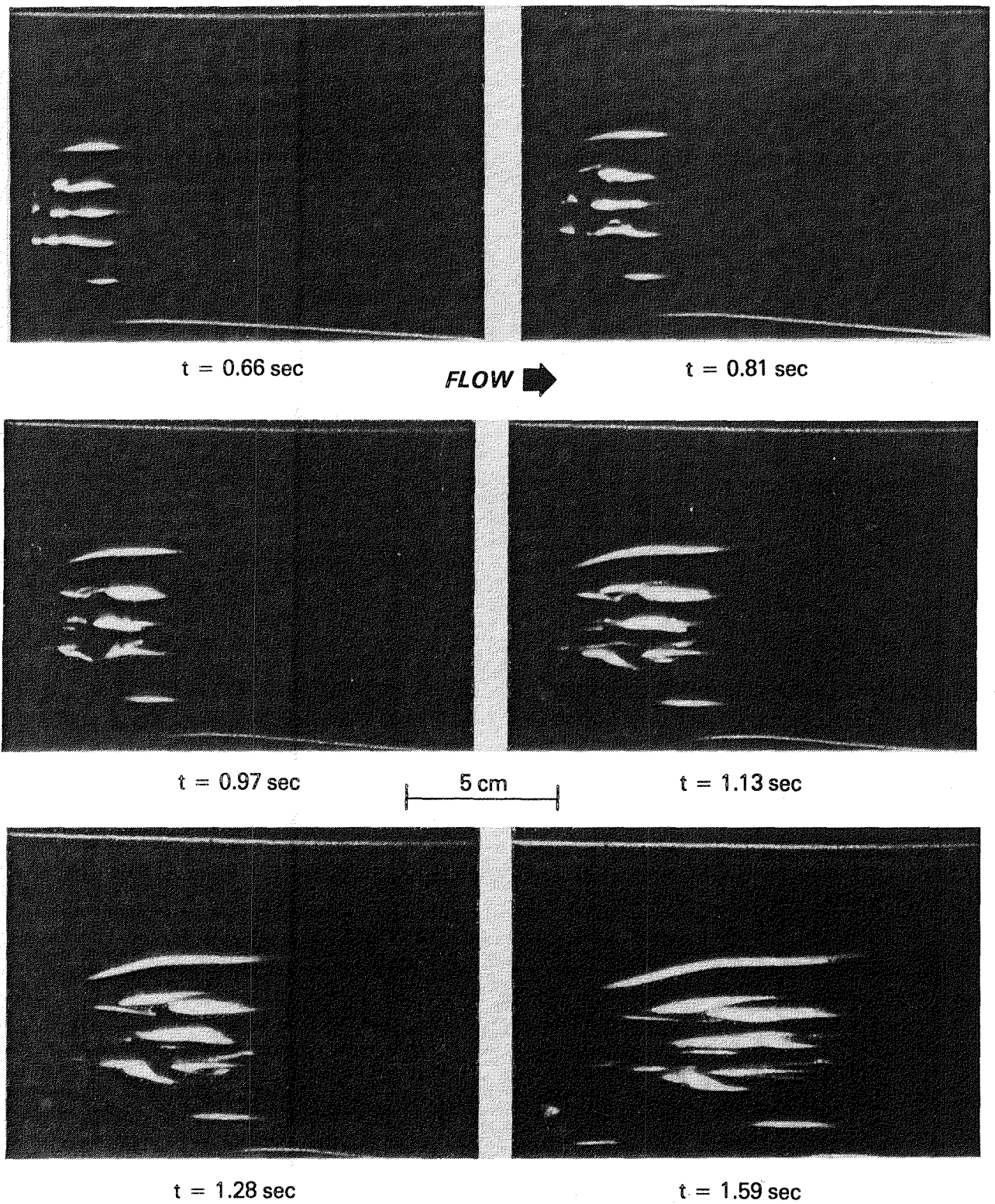


Figure 9. Withdrawing Fluid Through Four Suction Holes Results in the Generation of Five Low-Speed Streaks and Three Artificial Bursts

bursting events are observed. Three low-speed streaks are marked by the bright dye accumulation in Figure 7 for the case of two suction holes, but only the middle one breaks into a burst. In Figures 8 and 9, two and three unstable streaks are observed, respectively, for the case of three and four suction holes.

The hydrogen-bubble technique was also used to visualize the bursting events in a laminar boundary layer. Figure 10 shows a top view of the events resulting from withdrawing near-wall fluid through two suction holes separated in the spanwise direction. The hydrogen-bubble wire is perpendicular to the flow and parallel to the flat plate at a distance of 2 mm above the surface and 1 cm downstream of the suction holes. A horizontal sheet of laser light illuminates the bubbles. The low-speed regions are manifested as upstream kinks of the time lines, and longitudinal vorticity is indicated by the wrapping of these lines. The unstable region grows as it convects downstream and eventually breaks into a burst-like event.

A side view of the events depicted in Figure 10 is visualized using a vertical hydrogen-bubble wire and a vertical sheet of laser light. The fluid is withdrawn from the laminar boundary layer through the two suction holes located 1 cm upstream of the hydrogen-bubble wire. The resulting events are shown in Figure 11 for six time intervals after the onset of the artificial event. The undisturbed Blasius profile can be reconstructed from the time lines shed from the hydrogen-bubble wire. The formation, lifting and stretching of the hairpin vortex that results from distorting the originally spanwise vortex lines is clearly indicated in the pictures shown in Figure 11. The vortex head reaches the outer region of the laminar boundary layer about 1 sec after the suction has been initiated. The breakup of the vortex head is also indicated in the figure.

Artificial bursts were also generated by pitching a flush-mounted delta wing as shown in the schematic in Figure 12. The negative angle of attack of 30° leads to the formation of two longitudinal vortices. An unstable low-speed region is formed between the two vortices. The low-speed streak lifts up away from the wall, causing a strongly inflectional velocity profile, and rapidly breaks down into a completely random pattern much the same as the streaks generated by suction from spanwise holes.

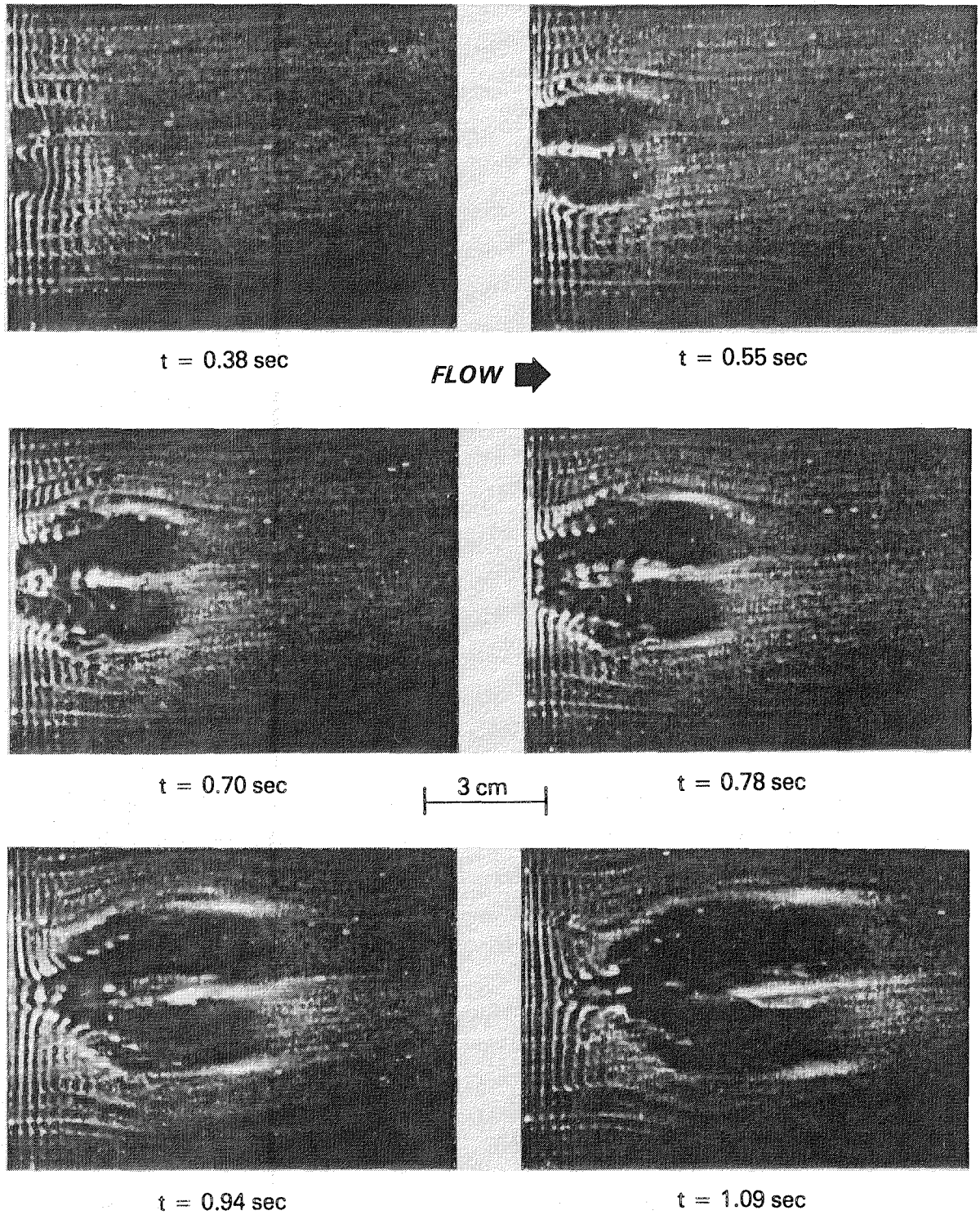


Figure 10. An Artificial Burst Generated by Withdrawing Fluid from Two Suction Holes and Visualized Using Hydrogen Bubbles and a Horizontal Sheet of Laser Light

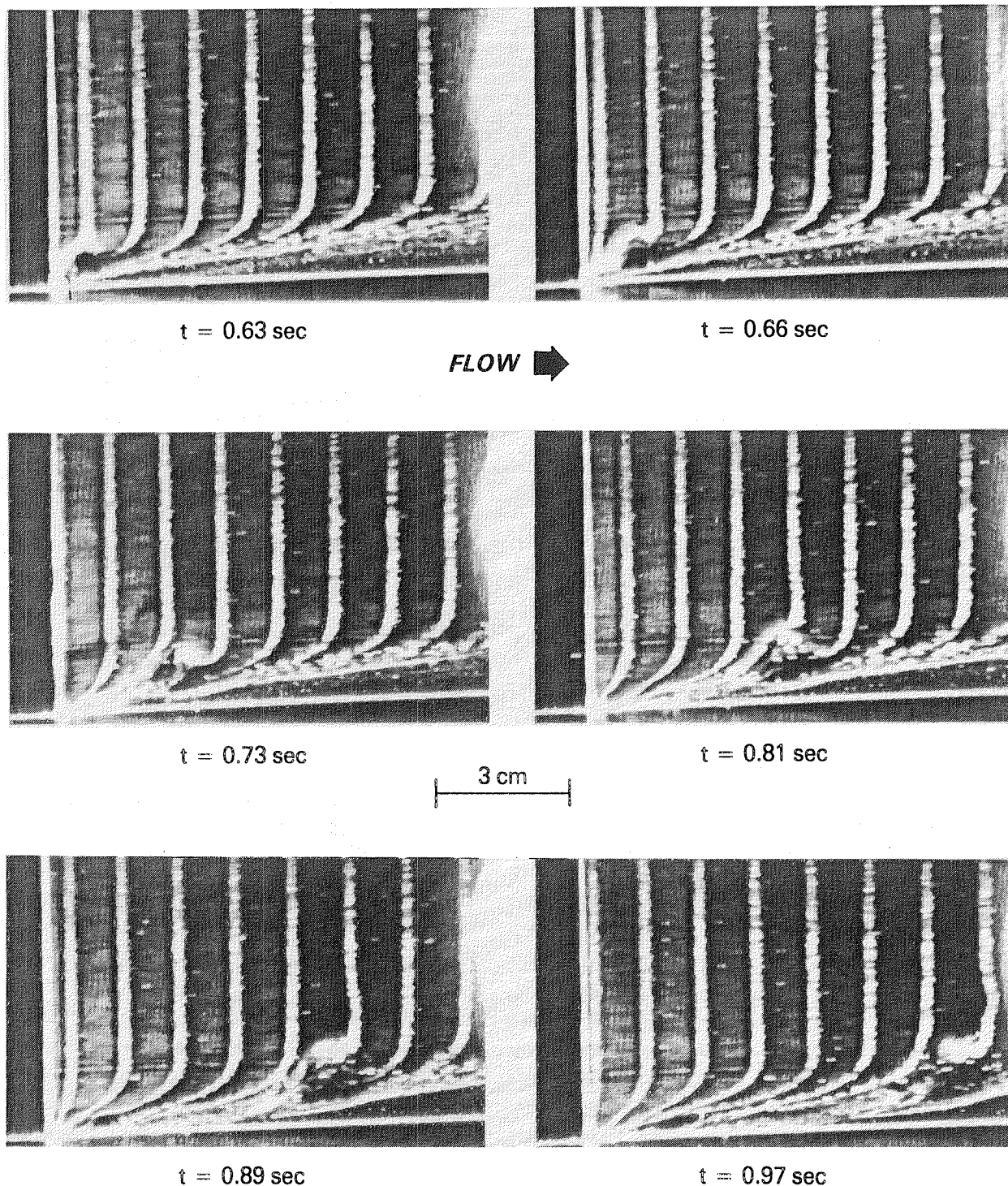


Figure 11. Side View of the Artificial Burst in a Laminar Boundary Layer Flow is Visualized Using Hydrogen Bubbles and a Vertical Sheet of Laser Light

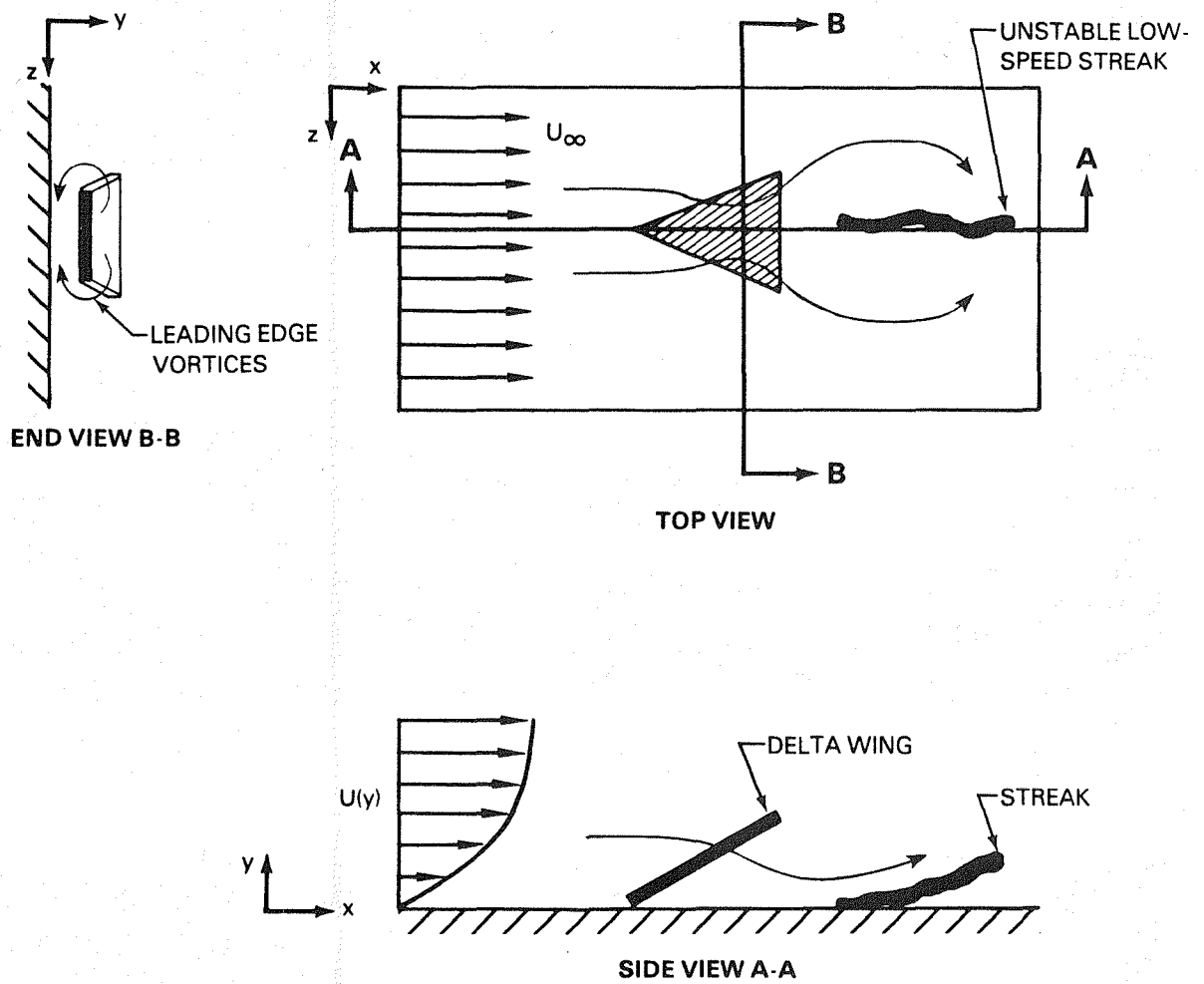


Figure 12. Artificial Burst Generation. Resulting Streamlines When a Delta Wing, Originally Flush with the Surface, is Impulsively Pitched to Generate Negative Lift

4. Bursts in a Turbulent Boundary Layer

A bursting event is, of course, a characteristic structure of a turbulent boundary layer. The artificial burst generators were used to generate burst-like events in a laminar flow as described in the previous section to allow easy visualization free of the random background that characterizes a turbulent flow. In this section, we describe the visualization of natural and artificial bursts in a turbulent boundary layer. The photographs in Figure 13 show the sequence of events leading to the breakup of a natural low-speed streak in a turbulent boundary layer. The wall region of the boundary layer is visualized by injecting fluorescent dye from the spanwise slot located just upstream of the view shown in the photographs. A horizontal sheet of laser at the wall clearly shows the natural low-speed streaks, manifested as bright regions of dye, with the typical spanwise spacing. In particular, the low-speed streak whose tail is marked with the vertical and horizontal arrows on the first photograph undergoes a large-amplitude oscillation at $t = 0.28$ sec (origin of time is arbitrary). At $t = 0.41$ sec, the breakup process has started, and it is completed at $t = 0.81$ sec, as shown in the last photograph in Figure 13.

The breakup of a natural low-speed streak is compared to that of the artificially generated one in Figure 14. Here, the origin of time coincides with the onset of suction from two spanwise holes. In the first frame, the vertical and horizontal arrows indicate the position of the midpoint between the two suction holes. A low-speed streak is formed due to the pumping action of the longitudinal vortices that result from distorting the originally spanwise vortex lines. The artificially generated low-speed streak undergoes oscillation and breakup much the same as the natural one. The similarity between the natural and artificial events is striking, considering the fact that the natural phenomenon under consideration is random in space and time.

A side view of the breakup of an artificially generated low-speed streak is shown in Figure 15. The turbulent boundary layer is visualized using fluorescent dye injected from the spanwise slot and a vertical sheet of laser light parallel to the flow. The dye accumulation near the wall indicates the formation of a low-speed region. In the first photograph in Figure 15, the streak lifts up as marked by the vertical arrow. The low-speed streak undergoes a large-amplitude oscillation and breaks up violently as shown in the sequence of movie frames.

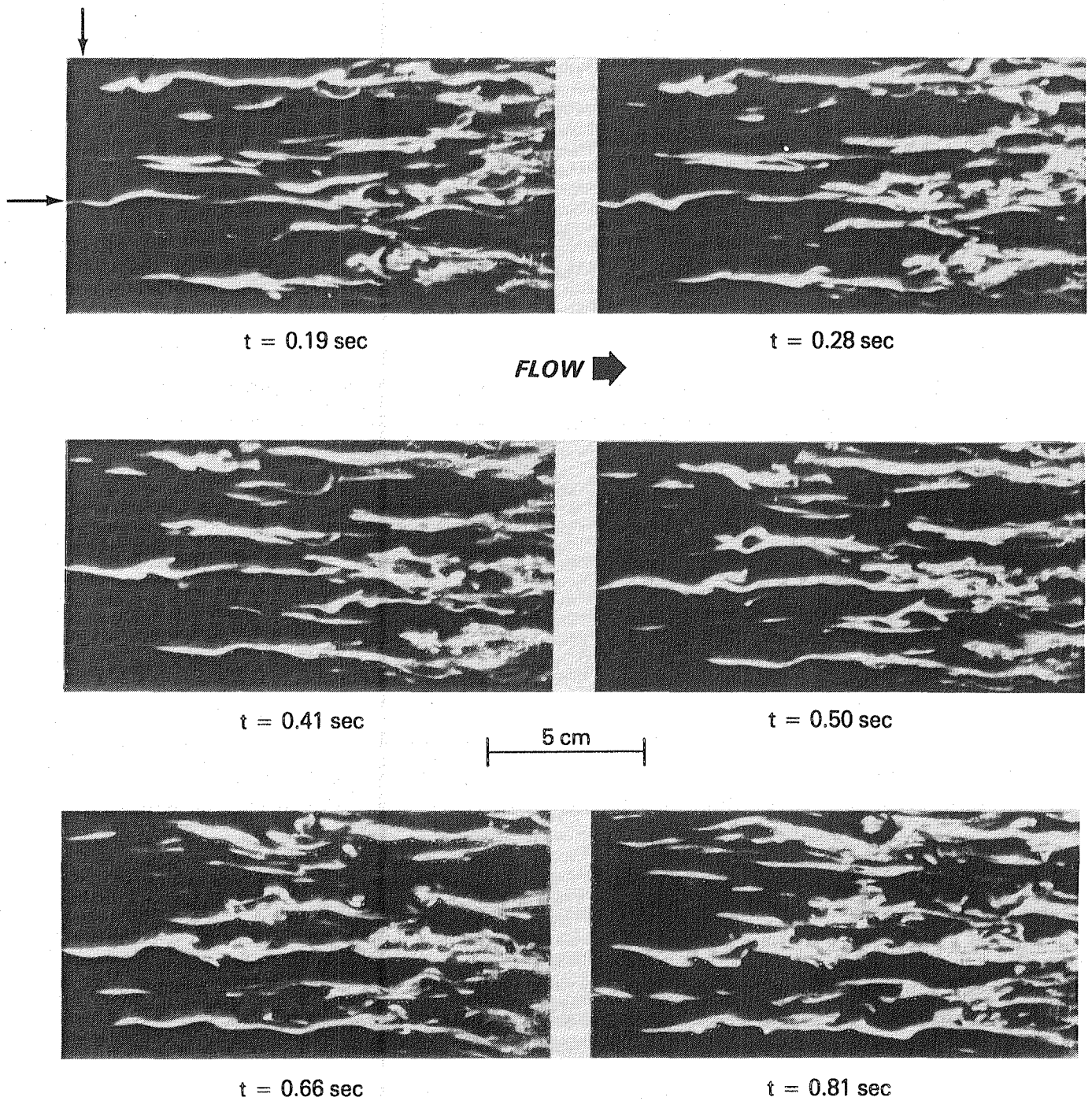


Figure 13. Top View of a Turbulent Boundary Layer Visualized Using Fluorescent Dye and a Horizontal Sheet of Laser Light. Sequence of Events Leading to the Break-Up of a Natural Low-Speed Streak

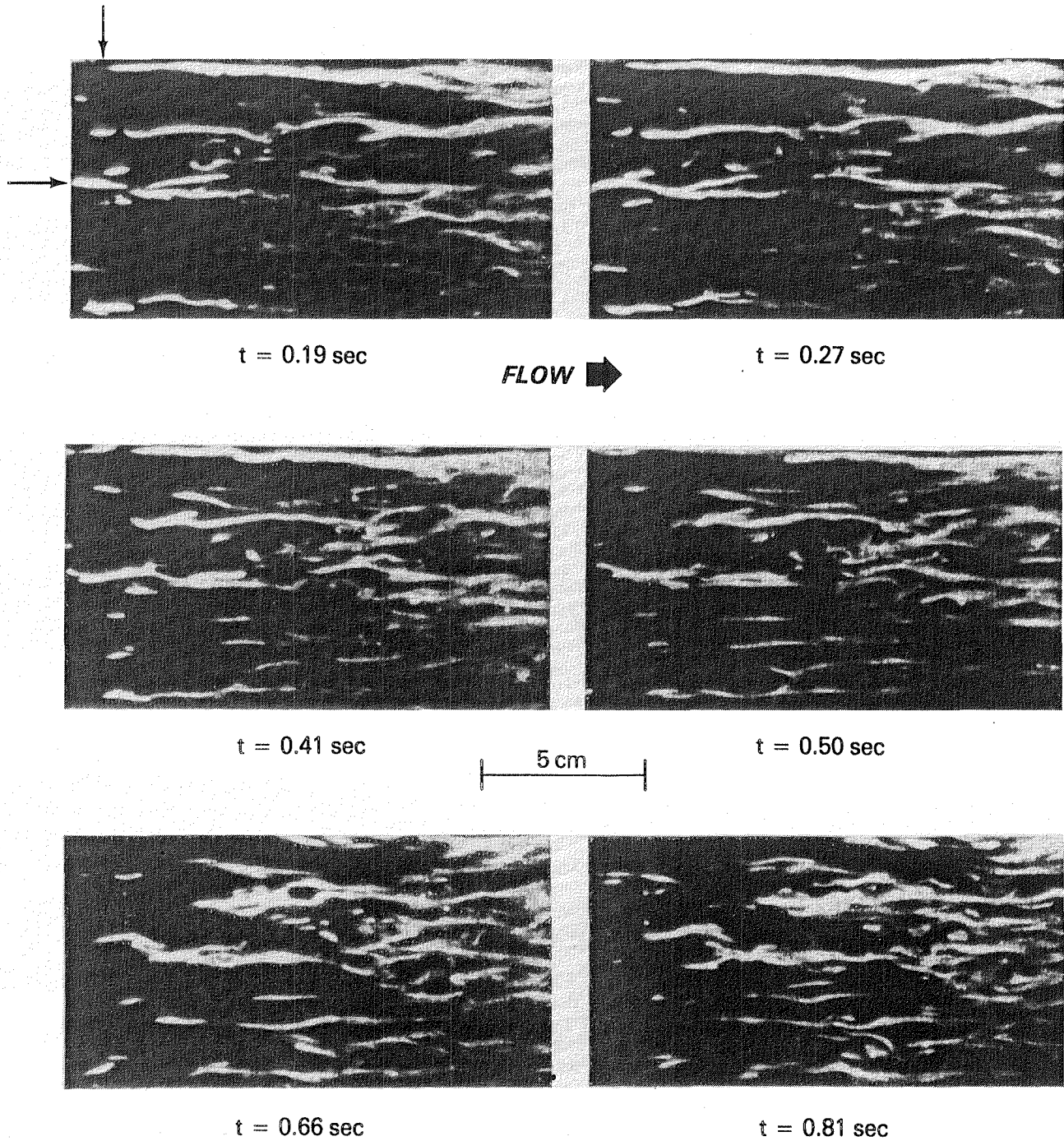


Figure 14. Top View of a Turbulent Boundary Layer Visualized Using Fluorescent Dye and a Horizontal Sheet of Laser Light. Sequence of Events Leading to the Break-Up of an Artificially-Generated Low-Speed Streak

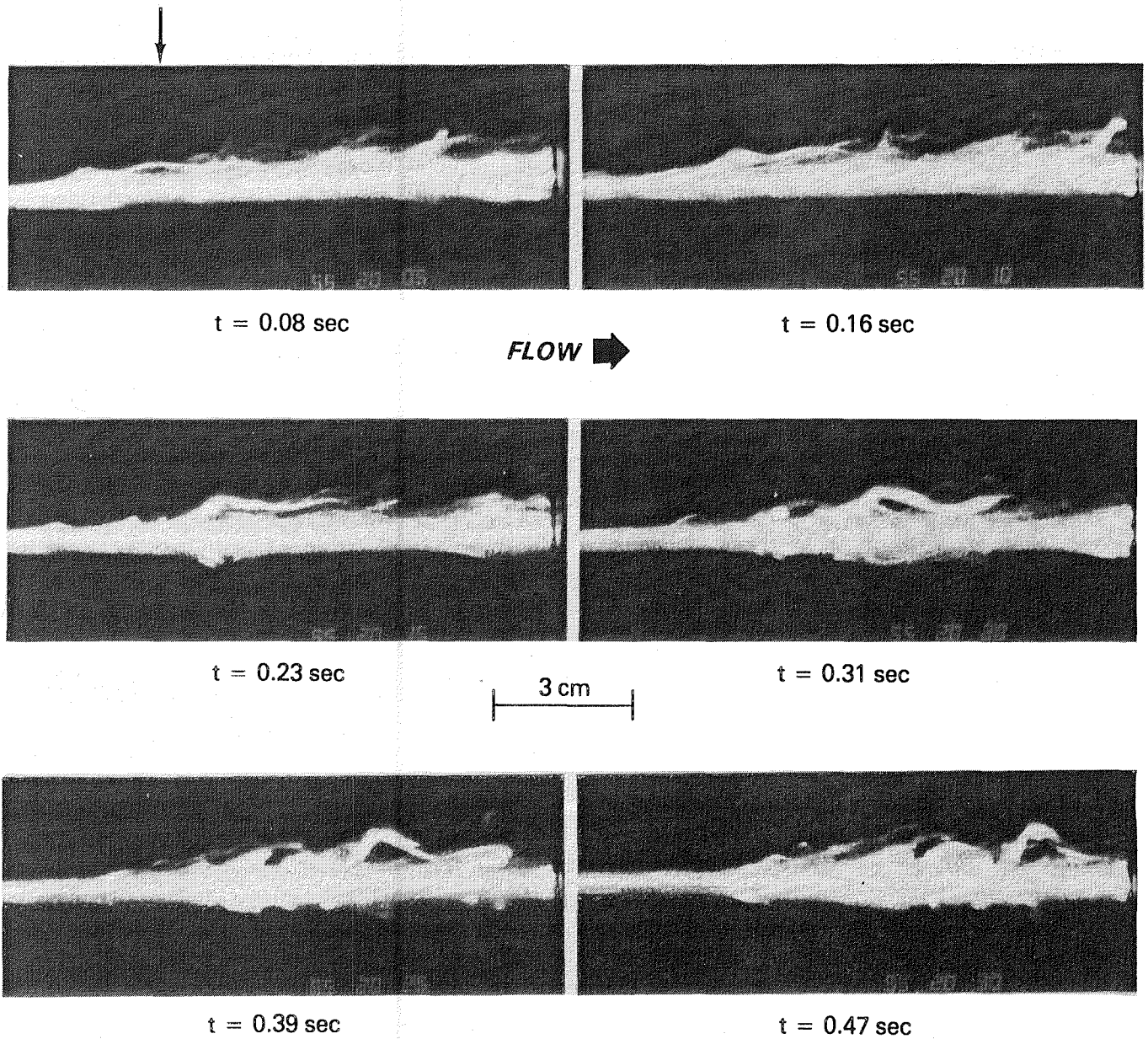


Figure 15. Side View of the Break-Up of an Artificially-Generated Low-Speed Streak. The Fluorescent Dye and the Vertical Sheet of Laser Light Show a Cut in the Hairpin Vortex Stretching and Lifting Away from the Surface

A different perspective of the natural and artificial bursts is obtained from side views using a vertical hydrogen-bubble wire and a vertical sheet of laser light. Figures 16 and 17 show the sequence of events leading to natural and artificially generated bursts, respectively. The formation of inflectional velocity profiles is clearly indicated in both figures. These profiles are inviscidly unstable, and the flow rapidly breaks down into a completely random pattern. It is interesting to note the different time scales associated with the bursting event in laminar and turbulent boundary layers (e.g., Figures 11 and 17). This is due to the different friction velocities and thus different viscous scales in the two boundary layers.

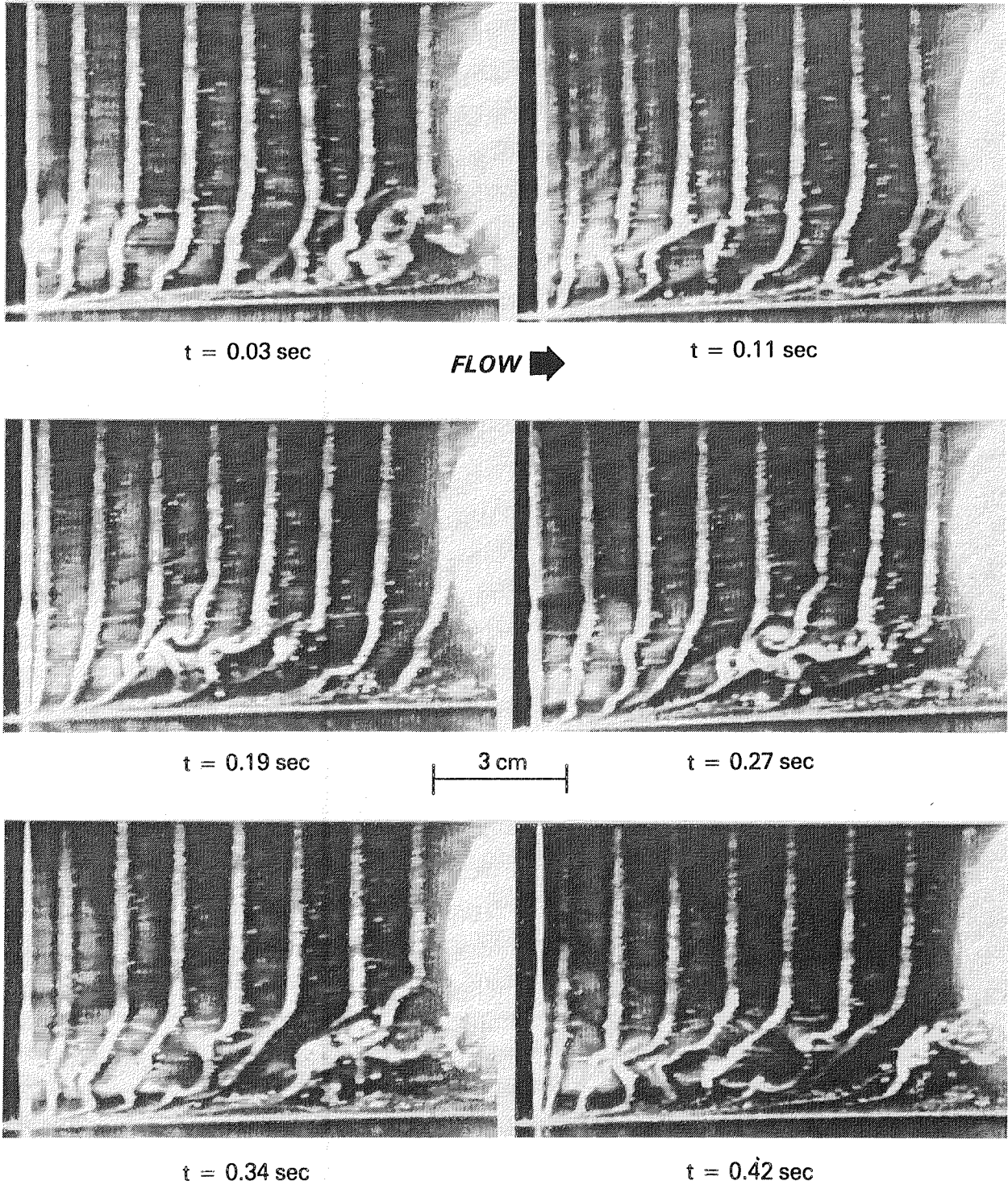


Figure 16. Side View of a Natural Burst in a Turbulent Boundary Layer Using Hydrogen Bubbles and a Vertical Sheet of Laser Light

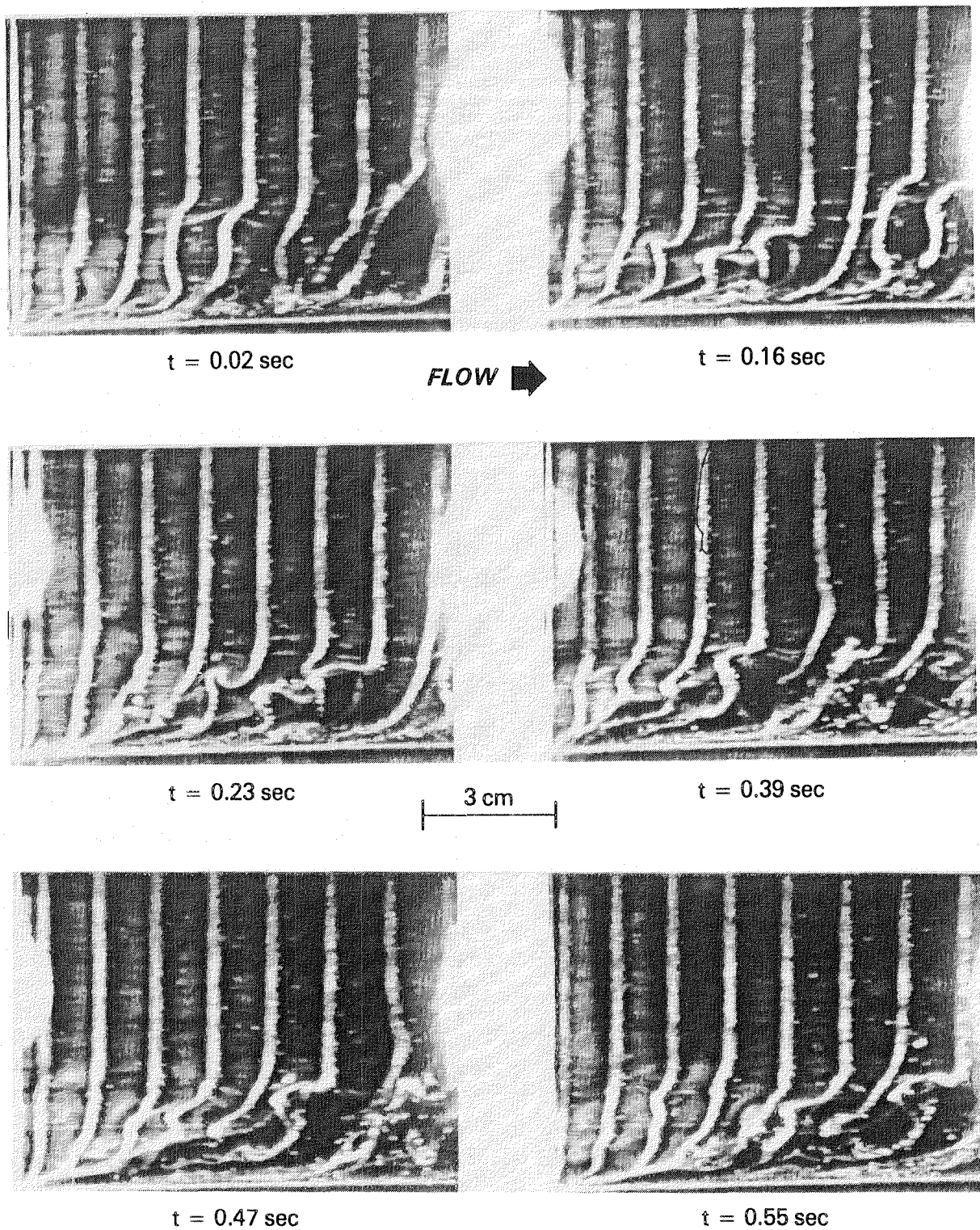


Figure 17. Side View of an Artificial Burst Generated by Withdrawing Fluid from the Turbulent Boundary Layer Using Two Suction Holes. The Flow is Visualized Using Hydrogen Bubbles and a Vertical Sheet of Laser Light

5. Pattern Recognition of Bursts and Streaks

The visualization results presented in Sections 3.3 and 3.4 indicate the sequence of events associated with the generation of an artificial burst in laminar and turbulent boundary layers, respectively. The observed flow patterns agree qualitatively with observations of naturally occurring bursts and streaks in a turbulent boundary layer. The length and time scales of the artificial events also agree with those for natural structures. For quantitative comparison between natural and artificial bursts, hot-film probes were used together with pattern recognition algorithms aimed at detecting low-speed regions and bursting events.

The miniature hot-film probes were first used to obtain mean and rms streamwise velocity profiles. In the laminar case, the mean velocity profiles were found to agree with the Blasius solution for a zero-pressure-gradient boundary layer. Similarly, the mean and rms velocity profiles in the turbulent case agreed well with those for a standard flat plate boundary layer. The mean profiles always had well-defined linear, logarithmic and wake regions. Clauser's (1956) method was used to determine the friction velocity used for normalizing the data and in the pattern recognition algorithms described below.

The hot-film probes used to detect the bursts and streaks were placed 100 to 1000 wall units downstream of the artificial burst generator, and at a height above the wall in the range of 10 to 20 wall units (a wall unit was about 0.1 mm at a freestream speed of 20 cm/sec and a streamwise distance from the leading edge of 80 cm). The instantaneous longitudinal velocity signal was mapped at these locations. In the laminar case, the initiation of an event using either the suction holes or the pitching delta wing was always associated with the passage of a velocity "spike" before the flow broke down into turbulence. These velocity spikes are consistent with the passage of the head of a hairpin vortex and are similar to the spikes observed by Klebanoff et al. (1962) in their classical vibrating ribbon experiment. In the case of a turbulent boundary layer, the artificial event caused a large streamwise velocity acceleration in the instantaneous velocity records similar to the accelerations observed by Blackwelder & Kaplan (1976) for natural bursts in a turbulent boundary layer. For a more objective assessment, the VITA technique was used to detect the passage of a burst; and the streak detection algorithm was used to recognize the formation and the evolution of a low-speed region. Both pattern recognition algorithms are reproduced in Appendix I.

The two pattern recognition algorithms, which have been described briefly in Section 3.2, search for recognizable patterns or structures. The burst detector searches for periods of high acceleration without necessarily larger fluctuations than the background turbulence. As shown by Blackwelder & Kaplan (1976), such periods are associated with events characterized by a high degree of coherence in time and in the direction normal to the wall and having a conditionally averaged Reynolds shear stress that is an order of magnitude greater than its conventionally averaged value. The detection scheme is then based on the dynamic properties of the organized structure. Similarly, the streak detector searches for low-speed regions near the wall relative to the background mean velocity.

Whenever the artificial burst generator was triggered, a low-speed streak and a burst were detected, after an appropriate time delay, by the two pattern recognition algorithms. This confirms our hypothesis that the artificial event is dynamically similar to a natural burst.

An important quantity to further confirm the dynamic similarity between natural and artificial events is the conditionally averaged Reynolds stress $\overline{\langle uv \rangle}$. This statistical quantity was not directly measured in the present preliminary investigation, but will be measured during the second phase of this work.

6. Summary

The objective of the Phase I work was to demonstrate the feasibility of generating artificial bursts in laminar and turbulent boundary layers. Experiments were conducted in FLOW's 18-meter towing tank. Zero-pressure-gradient laminar or turbulent boundary layers were generated by towing a flat plate in the water channel. Artificial bursts were generated by either withdrawing near-wall fluid from one, two, three or four minute holes separated in the spanwise direction, or by pitching a miniature delta wing that is flush-mounted to the wall of the plate. The resulting events were visualized using fluorescent dyes or hydrogen bubbles illuminated by a sheet of laser light projected in the desired plane. Both the suction and the pitching of the delta wing generated streamwise vorticity and one or more low-speed streaks. The unstable streaks lifted away from the wall, causing an inflectional velocity profile, oscillated and broke up into a burst.

Hot-film probes were used to measure the instantaneous longitudinal velocity, and the resulting signals were analyzed using two pattern recognition techniques that detect bursts and low-speed streaks. The two detectors consistently recognized a burst and a low-speed streak whenever the artificial burst generator was triggered.

The artificial events generated in this study are similar qualitatively and quantitatively to natural bursts in a turbulent boundary layer. We are now in a position to examine in detail the artificial bursts that occur at a given streamwise location in the boundary layer and at controlled times. The topological properties of the artificial bursts will be deduced from phase-locked hot-film measurements. Means of manipulating natural and artificial bursts for the purpose of boundary layer control and drag reduction will be contemplated during the second phase of this investigation.

By all available measures, Phase I of this project should be considered highly successful. We have been able to establish the proof-of-concept: the two-hole suction and the pitching delta wing do indeed produce longitudinal vortices and the associated longitudinal streaks of high-speed and low-speed fluids separated in the spanwise direction; the low-speed streak becomes unstable and breaks down in a way which appears to be identical with the bursting process. But Phase I has yielded a lot more: the dye injection method is successful in revealing the artificial bursting phenomenon; the hydrogen-bubble visualization is particularly helpful in obtaining a clear

perception of the time-evolution of the three-dimensional event; a series of holes separated in the spanwise direction can produce a series of simultaneous parallel streaks and bursting, etc., as discussed in Section 3. These results are more than what could be realistically expected during Phase I and are highly encouraging. They indicate that far greater successes are likely in Phase II.

The results of the Phase I work will be presented at the 38th Annual Meeting of the American Physical Society, 24-26 November, 1985, at the AIAA 24th Aerospace Sciences Meeting, 6-8 January 1986, and at the IUTAM Symposium on Fluid Mechanics in the Spirit of G. I. Taylor, 24-28 March 1986. A manuscript describing our experimental results will be sent to the Journal of Fluid Mechanics.

References

- Antonia, R. A. (1981) "Conditional Sampling in Turbulence Measurements," Ann. Rev. Fluid Mech. 13, p. 131.
- Blackwelder, R. F., (1978) "The Bursting Process in Turbulent Boundary Layers," Coherent Structures of Turbulent Boundary Layers, eds. C. R. Smith & D. E. Abbott, Dept. Mech. Eng., Lehigh University.
- Blackwelder, R. F., and Haritonidis, J. H. (1983) "Scaling of the Bursting Frequency in Turbulent Boundary Layers," J. Fluid Mech. 132, p. 87.
- Blackwelder, R. F., and Kaplan, R. E. (1976) "On the Wall Structure of the Turbulent Boundary Layer," J. Fluid Mech. 76, p. 89.
- Brodkey, R. S., Wallace, J. M., and Eckelmann, H. (1974) "Some Properties of Truncated Turbulence Signals in Bounded Shear Flows," J. Fluid Mech. 63, p. 209.
- Cantwell, B. J., Coles, D., and Dimotakis, P. E. (1978) "Structure and Entrainment in the Plane of Symmetry of a Turbulent Spot," J. Fluid Mech. 87, p. 641.
- Clauser, F. H. (1956) "The Turbulent Boundary Layer," Adv. Appl. Mech. 4, p. 1.
- Corino, E. R., and Brodkey, R. S. (1969) "A Visual Investigation of the Wall Region in Turbulent Flow," J. Fluid Mech. 37, p. 1.
- Falco, R. (1979) "Structural Aspects of Turbulence in Boundary Layer Flows," Symp. on Turb., U. of Missouri-Rolla, p. 1.
- Falco, R. E. (1980) "The Production of Turbulence Near a Wall," AIAA Paper No. 80-1356.
- Gad-el-Hak, M., Blackwelder, R. F., and Riley, J. J. (1981) "On the Growth of Turbulent Regions in Laminar Boundary Layers," J. Fluid Mech. 110, p. 73.

- Gad-el-Hak, M., Blackwelder, R. F., and Riley, J. J. (1984a) "On the Interaction of Compliant Coatings with Boundary Layer Flows," J. Fluid Mech. 140, p. 257.
- Hussain, A. K. M. F. (1980) "Coherent Structures and Studies of Perturbed and Unperturbed Jets," in Lect. Notes Phys. 136, ed. J. Jimeuer, p. 252.
- Hussain, A. K. M. F. (1983a) "Coherent Structures - Reality and Myth," Phys. Fluids 26, p. 2816.
- Hussain, A. K. M. F. (1983b) "Coherent Structures," Proc. Second Asian Congress of Fluid Mechanics, Beijing, p. 14.
- Hussain, A. K. M. F., and Reynolds, W. C. (1972) "The Mechanics of an Organized Wave in Turbulent Shear Flow. Part 2. Experimental Results," J. Fluid Mech. 54, p. 241.
- Hussain, A. K. M. F., and Zaman, K. B. M. Q. (1980) "Vortex Pairing in a Circular Jet Under Controlled Excitation. Part 2. Coherent Structure Dynamics," J. Fluid Mech. 101, p. 493.
- Klebanoff, P. S., Tidstrom, K. D., and Sargent, L. M. (1962) "The Three-Dimensional Nature of Boundary Layer Instability," J. Fluid Mech. 12, p. 1.
- Kline, S. J., Reynolds, W. C., Shraub, F. A., and Runstadler, P. W. (1967) "The Structure of Turbulent Boundary Layers," J. Fluid Mech. 30, p. 741.
- Kunen, J. M. G., Ooms, G., and Vink, P. J. J. (1983) "On Detection Methods for Coherent Structures in Turbulent Flows," Symp. on Turb., U. of Missouri-Rolla, p. 37.
- Nishioka, M., Asai, M., and Iida, S. (1981) "Wall Phenomena in the Final Stages of Transition to Turbulence," in Transition and Turbulence, ed. R. E. Meyer, Academic Press, p. 113.

- Offen, G. R., and Kline, S. J. (1975) "A Proposed Model of the Bursting Process in Turbulent Boundary Layers," J. Fluid Mech. 70, p. 209.
- Praturi, A. K., and Brodkey, R. S. (1978) "A Stereoscopic Visual Study of Coherent Structures in Turbulent Shear Flow," J. Fluid Mech. 89, p. 241.
- Sato, H. (1983) "Cognition and Description of Patterns in Turbulent Flows," Proc. Second Asian Congress of Fluid Mechanics, Beijing, p. 7.
- Smith, C. R. (1983) "A Synthesized Model of the Near-Wall Behavior in Turbulent Boundary Layers," Symp. on Turb., U. of Missouri-Rolla, p. 299.
- Willmarth, W. W. (1975) "Structure of Turbulence in Boundary Layers," Adv. Applied Mech. 15, p. 159.
- Wynanski, I. J., Sokolov, M., and Friedman, D. (1976) "On a Turbulent 'Spot' in a Laminar Boundary Layer," J. Fluid Mech. 78, p. 785.
- Zilberman, M., Wynanski, I., and Kaplan, R. E. (1977) "Transitional Boundary Layer Spot in a Fully Turbulent Environment," Phys. Fluids 20, p. S258.

Appendix I: Pattern Recognition Algorithms

```

C ***** PROGRAM TO COMPUTE THE CONVENTIONAL STATISTICS

C ***** PROGRAM TO COMPUTE THE CONVENTIONAL STATISTICS
C          AND STORE THE RESULTS IN AN INFORMATION BLOCK
C
C MODIFIED BY PAT MCCAFFERTY 850530 TO MAKE "IBA" INTEGER*4 TO
C PREVENT RMS BECOMING NEGATIVE WHEN T EXCEEDS 30 SECONDS
C WITH DT = .001 (32000 PTS INTEGER SHORT LIMIT)
C
    PARAMETER (LEN=11)
    REAL A(32),UBAR(LLEN),RMS(LLEN),C(4,LEN),B(128)
    REAL*8 SUMU(LLEN),SUMSQ(LLEN)
    REAL*8 AA,BB
    CHARACTER *32 FNAME
    CHARACTER *5 RUNO
    INTEGER*4 KCHN(5),LCHN(32),IBA
    INTEGER*2 IU(4096)
    DATA SUMU/LEN*0./,SUMSQ/LEN*0./,UBAR/LEN*0./,RMS/LEN*0./

C
C ***** READ INDX FILE
C
    PRINT *, 'ENTER LAST FIVE CHARACTERS OF RUN NAME'
    READ(1, '(A5)') RUNO
    FNAME='INDX/COAT'//RUNO
C PRINT *, ' FILE NAME IS ',FNAME
    OPEN(40, FILE=FNAME, STATUS='OLD', RECL=256, ERR=5,
    *FORM='UNFORMATTED', ACCESS='DIRECT')
    READ(40, ERR=5) (IU(K), K=1, 256)
    CLOSE(40)
    KCHN(1) = IU(181) /*TOTAL NUMBER OF CHANNELS RECORDED
    IF(KCHN(1).GT.LEN) STOP 'PROGRAM ONLY ACCEPTS 11 CHANNELS'
    KCHN(2) = IU(182) /*1ST CHN OF ADC'S USED
    CALL RN2P(IU(9),DT,INTL(1))
    WRITE(1,3) DT
3  FORMAT(/, ' DIGITIZING INTERVAL =',F8.5, ' SECONDS. ',/)
    A(21) = DT /*DIGITIZING INTERVAL
    CALL RN2P(IU(159),U00,INTL(1))
    WRITE(1,4) U00
4  FORMAT(' RECORDED VALUE OF U00 =',F6.1, ' CM/SEC. ',/)
    A(22) = U00
    GO TO 10
5  PRINT *, ' ERROR ENCOUNTERED IN READING',FNAME
C
C ***** READ THE COEFFICIENT FILE
C
10  FNAME='COEF/COAT'//RUNO
C PRINT *, ' COEFFICIENT FILE IS ',FNAME
    OPEN(31, FORM='UNFORMATTED', STATUS='OLD', FILE=FNAME)
    READ(31) B
    CALL RN2P(B,B,INTL(128))
    CLOSE(31)
    IC=4*KCHN(2) /*BIAS COEF TO FIRST CHAN RECORDED
    DO 20 K = 1,KCHN(1)
    LCHN(K)=K+KCHN(2)-1
    DO 20 J = 1,4

```

```

C ***** PROGRAM TO COMPUTE THE CONVENTIONAL STATISTICS

      IC = IC + 1
20    C(J,K) = B(IC)
      PRINT *, ' CHANNEL          A          B          C          D'
      WRITE(1,23) (LCHN(L), (C(J,L), J=1,4), L=1, KCHN(1))
23    FORMAT(I5,6X,4G10.3)
C
C ***** INPUT CHANNEL NUMBER OF HOT-FILMS
C
      PRINT *, 'TOTAL NUMBER OF CHANNELS RECORDED =', KCHN(1)
      CALL TNOUA(' ENTER CHANNEL NUMBER OF FIRST HOT-FILM: ',42)
      READ(1,*) KCHN(3)
      CALL TNOUA(' ENTER TOTAL NUMBER OF HOT-FILMS RECORDED: ',44)
      READ(1,*) KCHN(4)
      IFILM = KCHN(4)
C
C ***** SELECT THE TIME INTERVAL TO ANALYSE
C
      RECL = INT (4096/KCHN(1))*DT /*RECORD LENGTH IN SECONDS
      CALL TNOUA(' ENTER THE STARTING TIME[SEC]: ',32)
      READ(1,*) TSTART
      ISTART = TSTART/RECL+1
      TSTART = (ISTART-1)*RECL +DT
      PRINT *, 'TSTART =', TSTART
      CALL TNOUA(' ENTER THE STOPPING TIME[SEC]: ',32)
      READ(1,*) TSTOP
      ISTOP = TSTOP/RECL+1
      TSTOP = ISTOP * RECL
      PRINT *, 'TSTOP =', TSTOP
C
C ***** COMPUTE THE MEAN AND RMS VALUES OF ALL CHANNELS
C
      FNAME='DATA/COAT'//RUND
      ICH = KCHN(1)
      C2V=1./409.6
      C2V2=C2V*C2V
      C2V3=C2V2*C2V
      JBLK = 0
      IBA = 0
      LRCL=(4096/ICH)*ICH
      OPEN(29, FORM='UNFORMATTED', STATUS='OLD', FILE=FNAME, ERR=901)
40    READ(29, END=110, ERR=902) IU
      JBLK = JBLK + 1
      IF(JBLK.LT. ISTART) GO TO 40
      IF(JBLK.GT. ISTOP) GO TO 40
C      WRITE(1,11) (IU(M), M=1, LEN)
11    FORMAT(5I9)
C      ADD THE PRESENT DATA TO THE SUMMED STATISTICS
      IBA = IBA + 1
      DO 55 K=KCHN(3), KCHN(3)+KCHN(4)-1
      AA=0. DO
      BB=0. DO
      COF1=C(1, K)
      COF2=C(2, K)*C2V

```

C ***** PROGRAM TO COMPUTE THE CONVENTIONAL STATISTICS

```
      COF3=C(3,K)*C2V2
      COF4=C(4,K)*C2V3
      DO 50 J=K,LRCL,ICH
      V=FLOAT(IU(J))
      U=COF1+V*(COF2+V*(COF3+V*COF4))
      AA=AA+U
50    BB=BB+U*U
      SUMU(K)=SUMU(K)+AA
55    SUMSQ(K)=SUMSQ(K)+BB
C     PRINT *, ' FINISHING ',JBLK, ' PASS '
      GO TO 40
C
C ***** NORMALIZE THE DATA
C
      110 CLOSE(29)
      NORM = 4096/ICH
      XNORM = IBA*NORM /*NORMALIZATION FACTOR
      DO 200 K = KCHN(3),KCHN(3)+KCHN(4)-1
      UBAR(K) = SUMU(K)/XNORM
      XX = SUMSQ(K)/XNORM
      IF(XX - UBAR(K)**2) 190,195,195
190   PRINT *, ' NEGATIVE SQRT ON THE',LCHN(K), ' CHANNEL ==> RMS=0. '
      RMS(K) = 0.
      GO TO 200
195   RMS(K) = DSQRT(SUMSQ(K)/XNORM - UBAR(K)**2)
200   CONTINUE
C
C ***** OUTPUT THE DATA
C
      A(23) = JBLK
      A(24) = ISTART
      A(25) = ISTOP
      OPEN(32,FILE='BURST.DATA'//RUNO,FORM='UNFORMATTED')
      WRITE(32)A,C,UBAR,RMS,KCHN,FNAME /*WRITE INFORMATION ONTO DISK
      CLOSE(32)
      TREC = RECL*IBA
      XREC = RECL*JBLK
      WRITE(1,209) TREC,XREC
209   FORMAT(/,' THE MEAN STATISTICS FOR',F6.1,' SEC OF DATA ARE: '
      *,',5X'(THE TOTAL AVAILABLE RECORD IS',F6.1,' SEC.))
      WRITE(1,211) (LCHN(J),UBAR(J),RMS(J),J=1,ICH)
211   FORMAT(/,3X,'CHANNEL #   UBAR',9X,'RMS',/,12(4X,I7,2F12.2,/)
      CALL EXIT
C 901 DATA FILE OPEN ERROR
C 902 DATA FILE READ ERROR
      901 STOP 901
      902 STOP 902
      END
```

C PROGRAM (STREAK)

C PROGRAM (STREAK)

C ***** COMPUTES THE LOCATIONS OF LOW SPEED REGIONS FROM THE 3
C SPANWISE HOT-FILMS USING THE SECOND DERIVATIVE OF
C DU/DZ OR A THRESHOLD ON THE VELOCITY DATA AND
C PLOTS THE HISTROGRAM OF THE STREAK LENGTHS.
C THIS PROGRAM ASSUMES THE MEAN AND RMS STATISTICS
C HAVE BEEN CALCULATED AND STORED ON THE DISK.
C ----> CHANGING 'LENH' VARIES THE ABSCISSA OF THE HISTOGRAM
C ----> 'XAM' CONTROLS THE NOMALIZATION OF THE HISTOGRAM ORDINATE.

C
C PARAMETER (LEN=11)
C PARAMETER (LENH=60)
C REAL A(32), UBAR(LEN), RMS(LEN), C(4, LEN), B(128), OLDT, NOWT
C REAL UB(4096), U(3), UT(3)
C INTEGER*2 IU(4096), HIST(LENH), ICH(3)
C INTEGER*4 ITOT, ISAV, KCHN(5)
C CHARACTER AST, BLNK, LINE(60)
C CHARACTER*32 FNAME
C CHARACTER*5 RUNO
C DATA AST/'*'/, BLNK/' '/, LINE/60*'-'//, HIST/LENH*0/

C
C ***** READ IN STORED INFORMATION FROM THE DISK

C
C PRINT *, ' ENTER LAST FIVE CHAR OF RUN NAME : '
C READ(1, '(A5)') RUNO
C OPEN(32, FILE='BURST. DATA'//RUNO, FORM = 'UNFORMATTED',
C * STATUS='OLD')
C READ(32) A, C, UBAR, RMS, KCHN, FNAME /* INPUT STORED INFORMATION
C CLOSE(32)

C
C ***** SELECT THE 3 CHANNELS FOR THE STREAK ANALYSIS

C
C IF(KCHN(4).GT.2) GO TO 5
C PRINT *, ' LESS THAN 3 CHANNELS OF H. F. RECORDED !!! '
C STOP
5 WRITE(1,6) KCHN(3)
6 FORMAT(' THE FIRST H. F. SIGNAL IS ON CHANNEL #', I3, '. ')
C CALL TNOUA(' ENTER CHANNEL # OF FIRST H. F. TO ANALYSE : ', 43)
C READ(1,*) ICH(1)
C ICH(2) = ICH(1) + 1 /* ASSUMES H. F. CHANNELS ARE SEQUENTIAL
C ICH(3) = ICH(1) + 2 /* ASSUMES H. F. CHANNELS ARE SEQUENTIAL
C PRINT *, ' THE STREAK DETECTION WILL USE CHANNELS : ', ICH

C
C ***** SET UP PARAMETERS FOR DETECTING THE STREAKS

C
C NCH = KCHN(1) /* TOTAL # OF CHANNELS RECORDED
C RECL=INT(4096/NCH)*A(21) /* A(21)=DT
C THRES = 1. /* THRESHOLD USED FOR VELOCITY
C DO 10 K = 1, 3
10 ICH(K) = ICH(K)-KCHN(2)+1 /* BIAS ICH TO 1ST CHANNEL INDEX
C UT(1) = UBAR(ICH(1)) - 0.5*THRES*RMS(ICH(1)) /* VELOCITY THRESHOLD
C UT(2) = UBAR(ICH(2)) - 1.0*THRES*RMS(ICH(2)) /* VELOCITY THRESHOLD
C UT(3) = UBAR(ICH(3)) - 0.5*THRES*RMS(ICH(3)) /* VELOCITY THRESHOLD

C PROGRAM (STREAK)

```

ITOT = 0                   /* TIME COUNTER
OLDT = 0.                 /* STATUS WORD OF PREVIOUS DATA POINT
NOWT = 0.                 /* STATUS WORD OF PRESENT DATA POINT
GAMMA = 0.
IT = 0                    /* COUNTS NUMBER OF STREAKS
DT = A(21)                /* DIGITIZING INTERVAL
U00 = A(22)               /* TOWING SPEED
NBLK = A(23)              /* TOTAL # OF [4096] BLOCKS OF DATA
ISTART = A(24)            /* ISTART=FIRST BLOCK OF DATA TO ANALYSE
ISTOP = A(25)             /* ISTOP=LAST BLOCK OF DATA TO ANALYSE
CALL TNOUA(' ENTER THE VALUE OF UTAU[CM/SEC] : ',34)
READ(1,*) UTAU
PRINT *, 'STREAK STARTING TIME        STREAK STOPPING TIME'

C
C ***** BEGIN MAIN LOOP
C
   IBLK = NBLK
   LBLN = (4096/NCH)*NCH
   OPEN(29,FORM='UNFORMATTED',STATUS='OLD',FILE=FNAME)
   DO 210 IB = 1,IBLK
   READ(29,ERR=901) IU
   IF(IB.LT.ISTART) GO TO 210
   IF(IB.GT.ISTOP) GO TO 210
   CALL LINEAR3(IU,UB,C,ICH(1),NCH)
   DO 200 J = ICH(1),LBLN,NCH
   ITOT = ITOT + 1
   DO 30 K = 1,3
30   U(K) = UB(J+K-1)
   CR = U(3) - 2.*U(2) + U(1)       /* C = CURVATURE = 2ND DERIVATIVE
   IF(CR) 35,35,40                 /* IF C>0 ==>MINIMUM==>POSSIBLY STREAK
35   IF(U(1) - UT(1)) 38,38,150     /* STRONG DEFECT==>STREAK
38   IF(U(3) - UT(3)) 40,40,150     /* STRONG DEFECT==>STREAK
40   IF(U(2) - UT(2)) 60,60,150     /* STRONG DEFECT==>STREAK
C
C ***** STATEMENT 60==> THERE IS A SLOW SPEED REGION
C
60   NOWT = 1.
   GAMMA = GAMMA + 1.
   IF(OLDT.EQ.NOWT) GO TO 200
C ***** THIS IS A NEW LOW SPEED REGION
   DUMIB=IB
   DUMJ=J
   T1=((DUMIB-1.)+((DUMJ-1.)/4096.))*RECL
   IT = IT + 1
   ISAV = ITOT
   GO TO 190
C
C ***** STATEMENT 150==> THERE IS NO LOW SPEED REGION
C
150   NOWT = 0.
   IF(OLDT.EQ.NOWT) GO TO 200
C ***** THIS IS THE END OF THE LOW SPEED REGION
   DUMIB=IB

```

C PROGRAM (STREAK)

```
DUMJ=J
T2=((DUMIB-1.)+((DUMJ-1.)/4096.))*RECL
WRITE(1, '(2(5X, F8. 4))') T1, T2
LPOS = ITOT - ISAV
IF(LPOS. GT. LENH) LPOS = LENH
HIST(LPOS) = HIST(LPOS) + 1
190 OLDT = NOWT
200 CONTINUE
210 CONTINUE
CLOSE(29)
```

C

C ***** COMPUTE THE MEAN STATISTICS

```
TREC = ITOT*DT /* TOTAL RECORD LENGTH
PLS = UTAU*UTAU/0.01 /* NORMALIZING CONSTANT
IF(IT .EQ. 0) WRITE(1, 220)
IF(IT .EQ. 0) GO TO 901
220 FORMAT(' ***** NO STREAKS WERE DETECTED ***** ')
ALNGTH = GAMMA*DT/IT*PLS /* AVERAGE LENGTH IN T+
GAMMA = GAMMA/ITOT*100. /* INTERMITTENCY FACTOR
FREQ = IT/TREC /* FREQUENCY
FPLS = FREQ/PLS /* F+
WRITE(1, 251) RUNO, IT, TREC, GAMMA, FREQ, FPLS, ALNGTH
251 FORMAT(///, 10X, 'FOR RUN # ', A5, ', ', I5, ' STREAKS',
* ' WERE FOUND IN A ', /, 15X, 'TOTAL RECORD OF ', F7. 2,
* 'SECONDS. ', /, 20X, 'GAMMA =', F8. 2, '%', /, 20X
*, 'FREQUENCY =', F7. 1, ' HZ', /, 20X, 'F+', 8X, '=', F8. 4, /
*, 20X, 'LENGTH T+ =', F8. 1, /)
```

C

C ***** FIND THE MAXIMUM IN THE HISTOGRAM

C

```
MAX = 0
DO 300 I = 1, LENH
IF(HIST(I). LT. MAX) GO TO 300
MAX = HIST(I)
300 CONTINUE
340 XAM = FLOAT(MAX)/60.
C XAM = 1. ==>UNNORMALIZED HISTOGRAM
```

C

C ***** PLOT THE HISTOGRAM

C

```
DO 520 I = 1, 60
520 LINE(I) = '-'
WRITE(1, 551) LINE /* PRINT THE ORDINATE AXIS
551 FORMAT(//, 11X, 6(9X, ': '), /, ' LEN # ', 60A1)
DO 560 J = 1, 60
560 LINE(J) = BLNK /* ZERO THE LINE ARRAY
DO 600 I = 1, LENH
STL = I*DT*PLS /* STREAK LENGTH IN T+
JH = HIST(I)/XAM + 0.5 /* JH = SCALED ORDINATE OF HISTOGRAM
IF(JH. NE. 0) GO TO 575
WRITE(1, 566) STL, HIST(I) /* OUTPUT HISTOGRAM IF JH=0
566 FORMAT(F5. 1, I4, ' : ')
GO TO 600
```

```

C          PROGRAM (STREAK)

575  IF(JH.GT.60) JH = 60
      DO 580 J = 1, JH
580  LINE(J) = AST          /* PLACE '*' INTO LINE ARRAY
      WRITE(1,581) STL, HIST(I), LINE /* OUTPUT HISTOGRAM
581  FORMAT(F5.1, I4, ' : ', 60A1)
      DO 590 J = 1, JH
590  LINE(J) = BLNK        /* ZERO THE LINE ARRAY
600  CONTINUE
901  STOP 901
      END

C
      SUBROUTINE LINEAR3(IU, U, C, LCH, NCH)
C ***** LINEARIZES 3 DATA CHANNELS OUT OF A TOTAL NCH CHANNELS
C          IU = INPUT INTEGER ARRAY   U = OUTPUT REAL ARRAY
C          C = COEFFICIENT ARRAY     LCH = STARTING CHANNEL
      INTEGER*2 IU(4096)
      REAL U(4096), C(4, 11)
      LCH3 = LCH + 2
      DO 100 L = LCH, LCH3
      DO 100 I = L, 4096, NCH
      X = IU(I-1)/409.6
100  U(I) = C(1, L) + X*(C(2, L) + X*(C(3, L) + X*C(4, L)))
      RETURN
      END

```



```

C ***** THIS PROGRAM COMPUTES THE BURSTING TIMES AND

C ***** THIS PROGRAM COMPUTES THE BURSTING TIMES AND
C          REJECTS THE DECELERATIONS.
C
    PARAMETER (LEN=11)
    REAL A(32), UBAR(LEN), RMS(LEN), OLDT, NOWT, C(4, LEN), UB(5096)
    INTEGER*4 ITOT, ISAVE, KCHN(5)
    INTEGER*2 IU(5096), HIST(40)
    REAL*8 VITAE1, VITASQ, U, U1, AA, BB, V, W
    CHARACTER*32 FNAME
    CHARACTER *5 RUNO
    COMMON /DATA/IU
    DATA HIST/40*0/

C
C ***** READ IN STORED INFORMATION FORM DISK
C
    PRINT *, 'ENTER LAST FIVE CHAR OF RUN NAME : '
    READ(1, '(A5)') RUNO
    OPEN(32, FILE='BURST.DATA'//RUNO, FORM='UNFORMATTED',
    *      STATUS='OLD')
    READ(32) A, C, UBAR, RMS, KCHN, FNAME /*INPUT STORED INFORMATION
    CLOSE(32)

C
C ***** SELECT THE TRIGGER CHANNEL FOR THE VITA TECHNIQUE
C
    IF(KCHN(4)-1) 5, 9, 7
5    CALL TNOUA(' ENTER CHANNEL NUMBER OF FIRST H. F. : ', 38)
    READ(1, *) KCHN(3)
7    CALL TNOUA(' ENTER CHANNEL # OF H. F. TO ANALYSE: ', 38)
    READ(1, *) ICH
    GO TO 10
9    ICH = KCHN(3) /*ICH = CHANNEL # OF H. F.
10   PRINT *, ' CHANNEL #', ICH, ' WILL BE ANALYSED. '
C
C ***** SET UP PARAMETERS FOR VITA TECHNIQUE
C
    DT = A(21) /*DIGITIZING INTERVAL
    UOO = A(22) /*TOWING SPEED
    NBLK = A(23) /*TOTAL NUMBER OF [4096]BLOCKS OF DATA
    ISTART = A(24) /*ISTART = FIRST BLOCK TO ANALYSE
    ISTOP = A(25) /*ISTOP = LAST BLOCK TO ANALYSE
    NCH = KCHN(1)
    RECL=INT(4096/NCH)*DT
    ICH=ICH-KCHN(2)+1 /*BIAS ICH TO 1ST CHAN INDEX
    AVGU = UBAR(ICH)
    URMS = RMS(ICH)
    PRINT *, 'UOO =', UOO, 'UBAR =', AVGU, 'RMS =', URMS
    CALL TNOUA(' ENTER THE VALUE OF UTAU[CM/SEC]: ', 35)
    READ(1, *) UTAU
    DELT = 0.01/UTAU/UTAU
    NSAMP = 10.*DELT/DT
    NSAMP = (NSAMP/2)*2 /*MAKE NSAMP EVEN
    PRINT *, ' NSAMP = ', NSAMP
    NS = NSAMP/3*NCH

```

C ***** THIS PROGRAM COMPUTES THE BURSTING TIMES AND

```
FNSMP = 1./NSAMP
THRES = 1.0          /*TRIGGER LEVEL - 1.2 WAS USED BY RFB AND REK
ULEV = THRES*URMS**2
GAM = 0.            /*ZERO INTERMITTENCY
OLDT = 0.           /*OLDT IS THE FLAG FOR THE LAST DATA POINT
TRANS = 0.          /*# OF TRANSITIONS(I.E. BURSTS)
ITOT = 0            /*ITOT COUNTS THE RECORD LENGTH
VITAE1 = 0. DO      /*VITA SUM FOR MEAN VALUE
VITASQ = 0. DO      /*VITA SUM FOR MEAN SQUARE VALUE

C
PRINT *, 'BURST STARTING TIME      BURST STOPPING TIME'
C ***** BEGIN THE MAIN LOOP
C
IBLK = NBLK
LBLN=(4096/NCH)*NCH+1000
OPEN(29, FORM='UNFORMATTED', STATUS='OLD', FILE=FNAME)
DO 210 IB = 1, IBLK
READ(29, ERR=901)(IU(I), I=1001, 5096)
IF(IB.LT. ISTART) GO TO 210
IF(IB.GT. ISTOP) GO TO 212
CALL LINEAR(IU(1001), UB(1001), C, ICH, NCH)
DO 200 IC = ICH+1000, LBLN, NCH
ITOT = ITOT + 1          /*INCREMENT POSTITON COUNTER
U = UB(IC)-AVGU
U1=U
VITAE1 = VITAE1 + U      /*SHORT TIME AVERAGE OF U
VITASQ = VITASQ + U*U    /*SHORT TIME AVERAGE OF U**2
IF(ITOT.LE. NSAMP) GO TO 200
JC = IC - NSAMP*NCH
U = UB(JC)-AVGU
VITAE1 = VITAE1 - U      /*SUBTRACT OLD DATA POINT
VITASQ = VITASQ - U*U    /*SUBTRACT OLD DATA POINT
23  VARNCE = VITASQ*FNSMP - (VITAE1*FNSMP)**2 /*COMPUTE VARNCE
IF(VARNCE + .0001) 100, 110, 110
100 WRITE(1, 101) VARNCE, ITOT, IC, U, VITAE1, U1, VITASQ
101 FORMAT(F10.5, 2I8, 4F12.5, /)
XSTOP = XSTOP + 1
IF(XSTOP.GT. (NSAMP+10.)) STOP 'VARIANCE WAS NEGATIVE'
110 CONTINUE
IF(VARNCE - ULEV) 150, 160, 160
C ***** STATEMENT #150 IS FOR I(T) = 0
150 NOWT = 0.
IF(NOWT - OLDT) 155, 190, 190
C STATEMENT 155 IS EXECUTED WHEN EXITING FROM A BURST
155 TRANS = TRANS + 1          /*COUNT THIS LAST BURST
DUMIB=IB
DUMIC=IC-1000
T2=((DUMIB-1.)+(DUMIC-1.)/4096.)*RECL
WRITE(1, '(2(5X, FB.4))') T1, T2
ISAVE = 0
UMIN = 1000.
UMAX = -1000.
DO 157 I = JC, IC, NCH
```

C ***** THIS PROGRAM COMPUTES THE BURSTING TIMES AND

```
      IF(UB(I).LT.UMIN) UMIN = UB(I)
      IF(UB(I).GT.UMAX) UMAX = UB(I)
157  CONTINUE
      IH = UMAX - UMIN + 1.5
      IF(IH.LT.1) IH = 1
      IF(IH.GT.40) IH = 40
      HIST(IH) = HIST(IH) + 1
      GO TO 190
C ***** IS THIS AN ACCELERATION OR DECELERATION?
160  IF(UB(IC-NS) - UB(JC+NS)) 150,150,170 /*ELIMINATE DECELERATIONS
C ***** STATEMENT #170 IS FOR I(T) = 1, I.E. INSIDE A BURST
170  NOWT = 1.
      GAM = GAM + 1.
      IF(NOWT - OLDT) 190,190,180
180  ISAVE = ITOT /*SAVE BEGINNING COUNTER OF THIS BURST
      DUMIB=IB
      DUMIC=IC-1000
      T1=((DUMIB-1.)+((DUMIC-1.)/4096.))*RECL
190  OLDT = NOWT
200  CONTINUE
C ***** MOVE REMAINING DATA TO THE BEGINNING OF THE BUFFER
      LSPT = (4096/NCH)*NCH + 1
      JC = 0
      DO 205 IC = LSPT,LSPT+1000
      JC = JC + 1
205  UB(JC) = UB(IC)
210  CONTINUE
212  TREC = (ITOT - NSAMP)*DT /*TOTAL RECORD LENGTH
      BURSTS = TRANS /*NUMBER OF BURSTS
      FREQ = BURSTS/TREC
      FIN = FREQ*DELT
      GAMMA = GAM/ITOT*100.
      WRITE(1,213) THRES,BURSTS,GAMMA,FREQ,FIN
213  FORMAT(/,' THE BURSTING STATISTICS FOR THRESHOLD =',
1F4.1,' ARE: ',/,10X,'NUMBER OF BURSTS =',F10.0,
2/,10X,'INTERMITTENCY FACTOR =',F8.2,' %'
3/,10X,'FREQUENCY =',F19.2,' HZ',/,10X,'FREQ+ =',F26.5,/)
      CALL HSTER(HIST,40)
      CLOSE(29)
      CALL EXIT
C 901 DATA READ ERR
901 STOP 901
      END
C
      SUBROUTINE LINEAR(IU,U,C,ICH,NCH)
      INTEGER*2 IU(4096)
      REAL U(4096),C(4,11)
      DO 100 I = ICH,4096,NCH
      X = IU(I)/409.6
100  U(I) = C(1,ICH)+X*(C(2,ICH)+X*(C(3,ICH)+X*C(4,ICH)))
      RETURN
      END
C
```

C ***** THIS PROGRAM COMPUTES THE BURSTING TIMES AND

```

SUBROUTINE HSTER(HIST,N)
  INTEGER*2 HIST(N)
  CHARACTER LINE(40), BLNK, AST
  DATA BLNK/' ',AST/'*'/
C
C   LOCATE FIRST AND LAST POINT IN HISTOGRAM
C
  IMIN = N
  DO 20 I = 1,N
  IF(HIST(I).LE.0) GO TO 20
  IMIN = I
  GO TO 25
20  CONTINUE
25  IMAX = 0
  DO 30 I = 1,N
  IF(HIST(N+1-I).LE.0) GO TO 30
  IMAX = N + 2 - I
  GO TO 35
30  CONTINUE
35  WRITE(1,39)
39  FORMAT(//, ' HISTOGRAM OF THE MAXIMUM VELOCITY AMPLITUDE'
1, ' DIFFERENCE DURING ACCELERATION. ',//, ' CELL SIZE',
27X, '# OF',/,2X, '[CM/SEC]',6X, 'BURSTS',/)
  DO 100 I = IMIN-1,IMAX+1
  X = I - 1
  Y = X + 1.
  INUM = HIST(I)
  DO 80 J = 1,40
  IF(J.GT.INUM) GO TO 75
  LINE(J) = AST
  GO TO 80
75  LINE(J) = BLNK
80  CONTINUE
100 WRITE(1,101) X,Y,INUM,LINE
101 FORMAT(3X,F3.0,'-',F3.0,I10,2X,'!',40A1)
  RETURN
  END
```

Standard Bibliographic Page

1. Report No. NASA CR-4003		2. Government Accession No.		3. Recipient's Catalog No.	
4. Title and Subtitle Feasibility of Generating an "Artificial" Burst in a Turbulent Boundary Layer				5. Report Date August 1986	
				6. Performing Organization Code	
7. Author(s) Mohamed Gad-el-Hak				8. Performing Organization Report No. Report No. 332	
9. Performing Organization Name and Address Flow Industries, Inc. 21414- 68th Avenue, South Kent, WA 98032				10. Work Unit No.	
				11. Contract or Grant No. NAS1-17951	
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, DC 20546				13. Type of Report and Period Covered Contractor Report	
				14. Sponsoring Agency Code 505-60-31-04	
15. Supplementary Notes Langley Technical Monitors: J. B. Anders and D. M. Bushnell SBIR Phase I Final Report					
16. Abstract In this investigation, "artificial" bursts were generated in laminar and turbulent boundary layers. The burst-like events were produced by withdrawing near-wall fluid from two minute holes separated in the spanwise direction or by pitching a miniature delta wing that was flush-mounted to the wall. Either of these actions generated streamwise vorticity and a low-speed streak that resembled a naturally occurring one. The resulting sequence of events occurred at a given location and at controlled times, allowing detailed examination and comparison with natural, random bursts by means of flow visualization and fast-response probe measurement techniques.					
17. Key Words (Suggested by Authors(s)) Turbulent burst Turbulent boundary layers				18. Distribution Statement Unclassified - Unlimited Subject Category 34	
19. Security Classif.(of this report) Unclassified		20. Security Classif.(of this page) Unclassified		21. No. of Pages 54	22. Price A04

End of Document