A Color Video Display Technique for Flowfield Surveys

Allen E. Winkelmann* and Chen P. Tsao†
University of Maryland, College Park, Maryland

A computer-driven color video display technique has been developed for the presentation of wind tunnel flowfield survey data. The results of both qualitative and quantitative flowfield surveys can be presented in high-spatial-resolution color-coded displays. The display of data in this manner can be considered to be a new type of flow visualization. The technique enables one to present and interpret vast quantities of data that heretofore would have been difficult or impossible to comprehend. The technique has been used to display data obtained with a variety of heated element probes and pressure probes in surveys above and behind a wing with partially stalled and fully stalled flow.

Introduction

THE presentation of data obtained in surveys of a three-dimensional flowfield has always been a rather difficult task. A number of techniques have been developed through the years that have generally proved adequate to present test results in both a quantitative and qualitative fashion. For example, the velocity measurements taken in a three-dimensional (3D) boundary layer are typically presented in (quantitative) plots of the streamwise and cross-flow components. An isometric (3D) drawing of the 3D boundary-layer profile allows the reader to "visualize" the flowfield in a more qualitative sense, but this display is not well suited to present quantitative results. Point-by-point survey data taken in a plane are generally presented in the form of contour lines, the shading of regions, or the use of arrows to represent the direction and magnitude of velocity components. The construction of contour lines or the shading of regions of the survey plane involves interpolation schemes to fill in the areas between discrete data points.

In a technique developed recently by Crowder,[1,2] high-resolution survey data have been presented using color as the parametric variable. The technique involves mounting a set of light emitting diodes (LEDs) on a pitot probe, scanning the flowfield with the probe, and lighting the various colored LEDs (typically three) in response to the probe-transducer output. By taking a time-exposure photograph as the probe sweeps back and forth across the wind tunnel, a multicolored data display is obtained showing the variations of total pressure in the flowfield. With rapid scanning (and the use of a small spatial increment between scans), many scans are made, which results in good spatial resolution. Moreover, the method of recording allows the surveys to be made in any convenient fashion (such as scanning in circular arcs, etc.). Except for the circuit used to direct the lighting of the LEDs, no further data processing is needed and the photograph (or video recording) is the end product of the test.

Inspired by this work, a new method of data display for flowfield surveys has recently been developed at the University of Maryland.[3-5] In this technique, the probe is also scanned repeatedly across the flowfield (and incremented vertically by a small amount at the end of each scan) to obtain a "sheet" of high-spatial-resolution data. The transducer output from a given probe is recorded on tape and processed through a computer, which color codes the data and then displays the results on a color video monitor. Specific regions of interest can be magnified and reassigned additional colors simply by reprocessing the data stored on magnetic tape. Depending on the type of data to be displayed, 20-30 distinguishable colors can be used.

Since this technique is generic, virtually any type of probe can be used depending on the type of flowfield survey being conducted. The use of a single-element hot-wire probe in the study of a highly separated flowfield (e.g., behind a wing at a high angle of attack) will yield data that is highly qualitative [i.e., no hard numerical values (velocities) can be assigned to the data]. On the other hand, if our "probe" is a three-channel laser velocimeter, then with proper data processing, we can obtain hard quantitative data (i.e., the complete 3D velocity field).

The color video display technique for flowfield surveys is another example of the use of color coding for the presentation of vast quantities of complex data. Color-coded video display techniques have been in use for years in satellite imagery, infrared thermography, and medical CAT scans. The use of color shading provides an added "degree of freedom" that greatly expands one's comprehension of large data sets.

After completion of the present work, the authors became aware of a similar technique developed by Anderson et al.[6] that was used to display rake data obtained in a mixer nozzle.

Experimental Program

The color video display technique has been utilized in several different test programs at the University of Maryland (e.g., Refs. 3-5). The test program to be discussed in this paper involved a study of the flow phenomenon associated with a partially stalled and a fully stalled finite wing.[4,5] An extensive series of flow visualization and flowfield survey tests were conducted to obtain an insight into the complex separated flowfield produced by the stalled wing. A detailed description of the color video display technique, as applied in this test program, will be presented in the following sections.

Figure 1 shows a sketch of the finite wing model mounted in the front section of the 1.17×0.46 m aerospace boundary-layer tunnel. The wing model has an aspect ratio $\text{Æ} = 4$ and a 15.24 cm chord Clark Y-14 airfoil section. Flowfield surveys were made using a traversing rig mounted on top of the wind tunnel (Figs. 1 and 2). The traversing rig could be mounted across the tunnel to make spanwise surveys or along the tunnel to permit chordwise surveys. The main carriage of the

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*Associate Professor, Department of Aerospace Engineering. Member AIAA.

†Graduate Research Assistant, Department of Aerospace Engineering. Student Member AIAA.

traversing rig moves back and forth on Thomson linear bearings, being pulled by a small dc motor and Winfred Berg Min-E-Pitch chain. A 10 turn potentiometer on the opposite end monitors the location of the carriage. At the end of each scan across the tunnel, the vertical carriage can be incremented upward using a stepper motor. A geared dc motor/potentiometer system mounted on the vertical carriage allows for rotation of a probe mounted in the stem holder.

In this paper, data will be presented from three test series: 1) spanwise surveys above and behind the wing using a single-element hot-wire probe and a Conrad probe, 2) chordwise surveys on the wing center plane using a hot-wire probe and a split-film probe, and 3) spanwise surveys at one station using a five-tube pressure probe. All tests were conducted at a Reynolds number based on chord of $Re_c = 480{,}000$.

The spanwise surveys using the hot-wire probe and the Conrad probe (a two-tube wedge-shaped pressure probe) were made in vertical increments of 2.68 mm. A survey was started well below the horizontal projection of the trailing edge (for downstream surveys) and continued upward until the output being monitored on an X-Y plotter appeared nearly uniform across a scan. The scanning rates were typically 1.2 cm/s with a 68.6 cm scan taking approximately 57 s. The data, which were recorded on a 14 track Racal analog tape recorder, were processed through three computer systems as shown in the block diagram in Fig. 3. The hot-wire data (linearized dc output) and the Conrad probe (pressure transducer) data were recorded at a tape speed of 9.53 cm/s. The spanwise location of the main traverse carriage (monitored by a 10 turn potentiometer) was recorded on a second channel of the tape recorder. The vertical increment of each scan was constant for a given test and was simply keyed into the computer before processing the data. A scan was initiated by an "on" switch that fed a signal from a 6 V battery onto a third track of the recorder. The on/off switch was turned off when the scan ended. The analog tape was played back through the HP-1000 computer system for analog-to-digital (A/D) conversion. The on/off switch essentially told the computer when to look at the incoming data. For a typical spanwise scan of $y = 68.6$ cm, the HP-1000 A/D system produced about 3800-4000 digital data points. The scan was divided into 512 spatial increments and 7-8 data points were assigned to each increment. An average of the data in each spatial increment (a pixel for the subsequent video display) was calculated and stored on digital tape. A UNIVAC 1140 computer system was then used to color code the data after 15 equal voltage increments were selected (ranging from the minimum to maximum voltage outputs from the probe/transducer). Three binary files were then created for the standard RGB (red, green, blue) output of the UNIVAC system. A PDP-11/Grinnell image processing system was finally used to display the three files, which resulted in a color video picture of the flowfield survey. The selection of the 15 colors was made solely on the basis of which combination seemed to give the most graphic and colorful displays. The video screen was photographed using a well-aligned 35 mm camera with a low ISO film (e.g., ISO 64 or 100), f-stop settings of f11-f22 and 1 s exposure.

Chordwise hot-wire and split-film surveys were obtained on the centerplane of the fully stalled wing at an angle of attack of $\alpha = 28.4$ deg. The split-film probe (model 1288 manufactured by Thermo-Systems, Inc.) was used to measure the percentage of time that the flow contained a velocity component in the upstream direction (essentially the percentage of time that the flow was "reversed"). The split-film probe was mounted in the tunnel such that one sensor was perpendicular to and facing the freestream velocity vector. The output from the two hot-film circuits was fed through a differencing unit to give the difference in output between the two sensor elements. The circuits were adjusted in a pretest calibration such that a reversed flow component would be recorded as a negative input to the tape recorder. The processing through the computer then involved determining the percentage of data points in each pixel that was negative and assigning a percentage of time the flow was reversed to each pixel. Because of data handling problems on

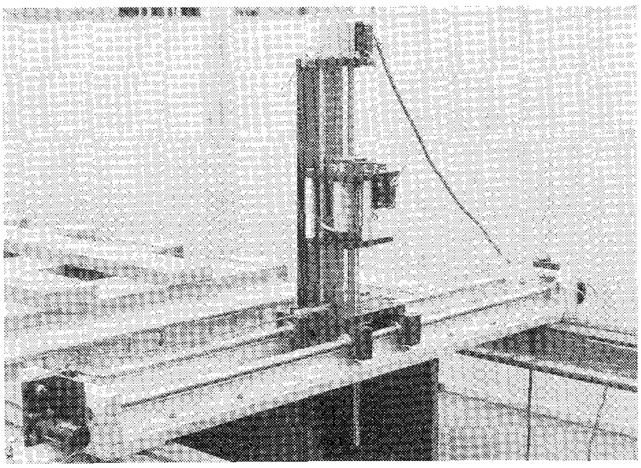


Fig. 2 Traverse device.

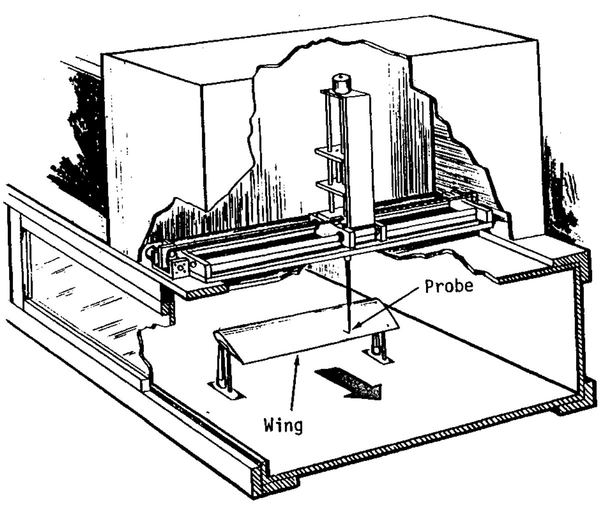


Fig. 1 Wing model and traverse device in wind tunnel.

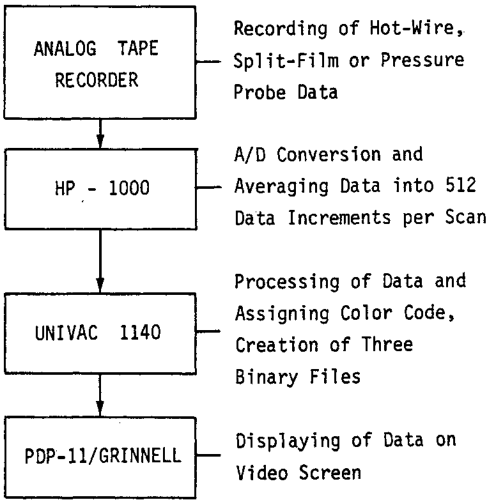


Fig. 3 Flow chart of data reduction for color video display technique.

the HP-1000 system, only about 10 data points per pixel were involved in calculatng a percentage of time the flow was reversed. Hence, the resolution of these data is considered rather coarse. In all of the chordwise surveys, the probes were manually driven typically to within 2 mm from the surface of the wing. If the traverse rig was modified to be operated by a microcomputer, then the probes could be driven up to the surface automatically, once the wing surface coordinates were programmed into memory.

Preliminary flowfield survey results were also obtained downstream of the wing using a scanning five-tube pressure probe. The probe tip used in these tests consisted of five tubes (0.71 mm o.d. $\times$ 0.41 mm i.d.) silver soldered together and machined off to produce a 70 deg included angle cone. By scanning at a low rate (0.6 cm/s), the probe was automatically nulled out in yaw. The output from a differential pressure transducer was used as input to an analog circuit that in turn operated the dc motor/potentiometer mechanism on the vertical carriage of the traverse device. With this device, the probe was typically aligned to within ± 3 deg of the local yaw angle β. In this test, eight tracks of data were recorded, which included the outputs from five pressure transducers, the spanwise location, the yaw angle β, and an "on" switch indication. The "on" signal initiated sampling by a Phoenix A/D data system that had sample and hold capabilities. Approximately 3500 data points per track were obtained for each scan. Further processing of the data, including the use of transducer and probe calibration data, was performed on the UNIVAC 1140 computer. For preliminary processing of the initial test data, β was calculated directly from the traverse potentiometer reading. The

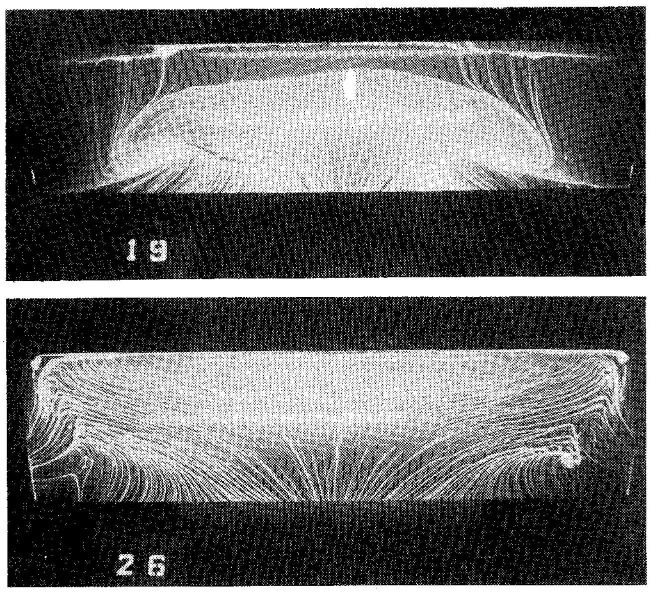


Fig. 4 Oil flow patterns on a partially stalled (top) and a fully stalled (bottom) wing.

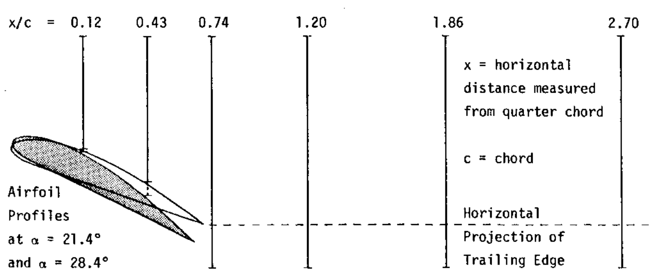


Fig. 5 Location of spanwise survey stations above and behind wing.

local pitch angle θ and the local value of dynamic pressure were determined from calibration curves for the probe.

Results and Discussion

Experimental studies of the flowfield associated with the partially stalled and fully stalled $AR = 4$ wing have involved the use of a variety of flow visualization techniques, such as surface oil, smoke, tuft wands, etc.[4,5] The surface oil flow visualization photographs, included in Fig. 4, indicate the complex nature of the separated/reversed flowfield occurring at the partially stalled ($\alpha = 21.4$ deg) and the fully stalled ($\alpha = 28.4$ deg) conditions. Of particular interest are the strong counterrotating swirl patterns formed in the trailing-edge stall cell at $\alpha = 21.4$ deg. The shape of the separation cell has led to the name "mushroom stall cell."[7] A flowfield model proposed in Ref. 7 suggests that the swirl patterns are created by the time-averaged effect of vortex-like flows that attach to the wing surface. Flow visualization tests using tuft wands, smoke probes, and water probes suggest that a recirculating region exists above and behind the partially stalled and the fully stalled wing.

Spanwise flowfield surveys using a hot-wire probe were made at six stations above and behind the wings at $\alpha = 21.4$ deg and $\alpha = 28.4$ deg as shown in Fig. 5. The hot-wire probe was mounted with the stem in the vertical position (i.e., in the cross flow) with the hot-wire element perpendicular to the freestream flow direction. In addition to hot-wire surveys, data were also obtained using a Conrad probe at the $x/c = 2.70$ survey station to obtain a qualitative indication of the variation of pitch in the flowfield.

Figure 6 shows a composite of the hot-wire and Conrad (pitch) probe data taken above and behind the wing. These displays are views of the "sheets" of data from a vantage point downstream of the wing. The surveys made above the wing started at 2.54 mm off the surface. For surveys made behind the wing, the horizontal projection of the trailing edge is shown as a white line. The data in these displays are highly qualitative because of the unsteady three-dimensional reversed flow in the separated wake regions—the variations in voltage output of the hot-wire probe may be due to variations in speed and/or flow direction. The Conrad probe indicates only the general trends of pitch variations in the flow because it is also sensitive to cross flow. In some sense, these displays can be considered to be a new type of flow visualization.

Unfortunately, the black-and-white reproduction of these data sets prevents one from clearly discussing these results in terms of the specific colors existing in the displays. In the remainder of this paper, reference to color levels in the data will be made in an attempt to convey to the reader what can be seen in the actual color displays.

For both the hot-wire probe and the Conrad probe, the data were color coded such that shades of red corresponded to the minimum output voltage levels and shades of pink to the maximum levels. Intermediate output levels were presented in shades of green to blue. Minimum output levels for the hot-wire probe indicated low-speed and/or high-angle flow; maximum output levels indicated high-speed and/or low-angle flow. For the Conrad probe data, minimum output levels indicated upward flow ($+\theta$) and maximum output levels indicated downward flow ($-\theta$).

In the hot-wire data shown in Fig. 6, the outlines of the developing separation bubble over the upper surface of the wing are very apparent as regions of red to yellow colors, indicating low-speed and/or high-angle flow relative to the hot-wire element. A slight distortion of the wake flow above and behind the wing at $\alpha = 21.4$ deg is apparent in these displays (this distortion is also seen in the oil flow pattern of the "mushroom stall cell" in Fig. 4). Regions of concentrated red to both sides of the separation bubble are thought to be associated with a vortex flow that appears to attach to

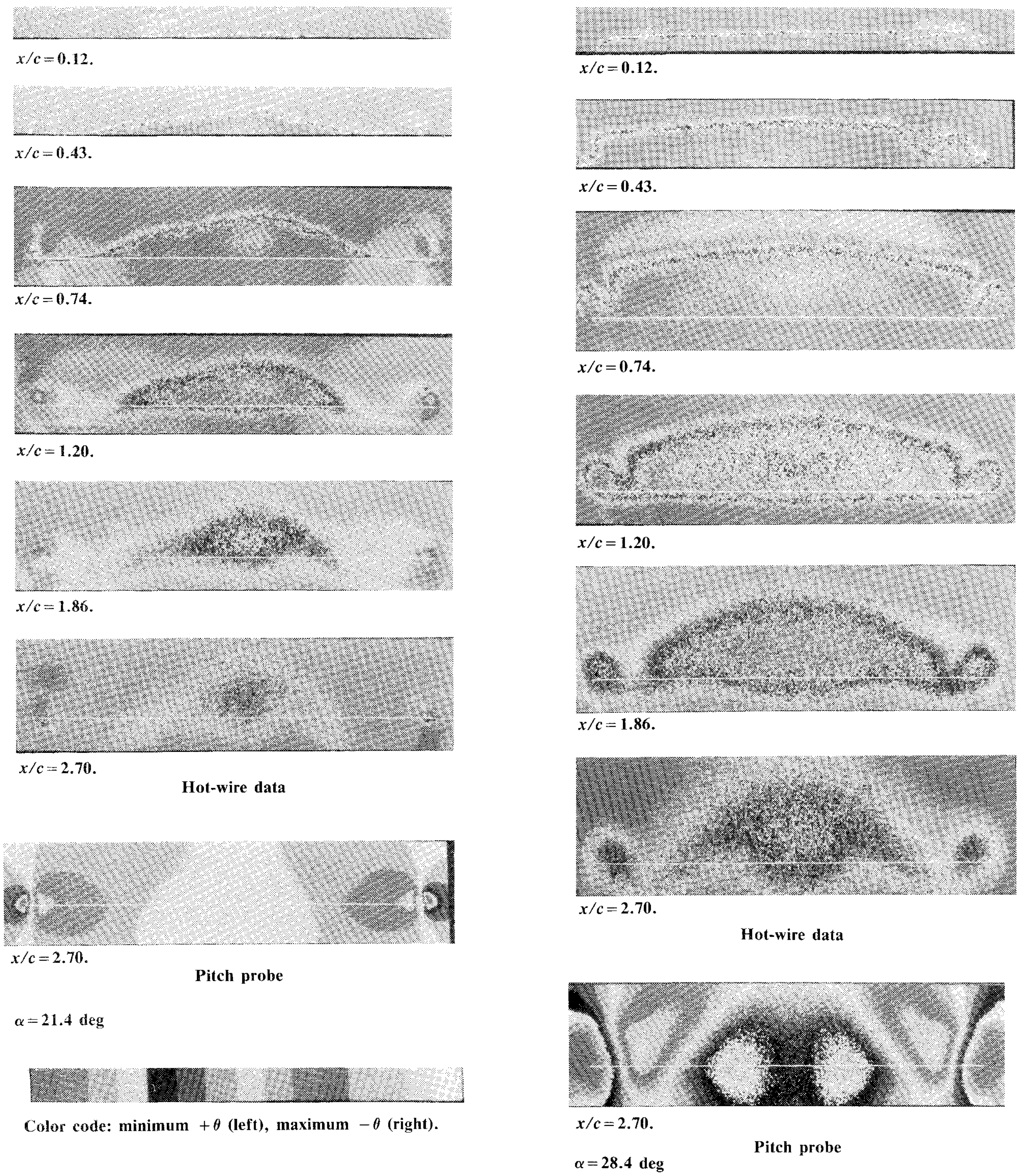
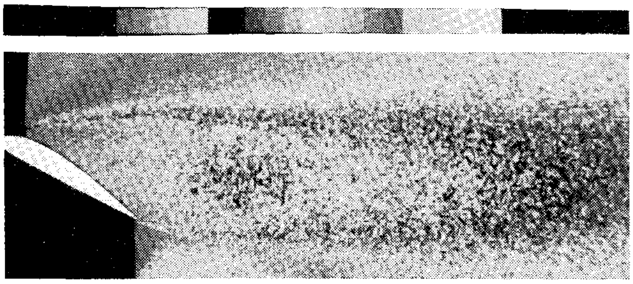


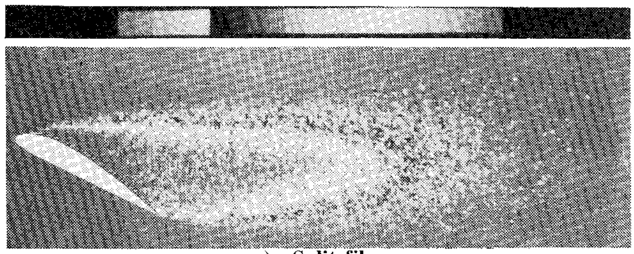
Fig. 6 Color video displays of hot-wire and Conrad (pitch) probe surveys above and behind a partially stalled and a fully stalled wing (x referenced to $c/4$).

the wing at the location of the oil swirl patterns. For the fully stalled wing, a region of pink occurs over the separation bubble, indicating high-speed flow due to blockage effects. With increasing distance downstream, the wake flow associated with the separation bubble eventually fades away for the partially stalled wing and closes in for the fully stalled case. The tip vortices for the partially stalled wing appear in pink, indicating high-speed flow, despite the high flow angles also occurring in this region. For the fully stalled wing, the tip vortices appear to be forming at the second survey station and seem to be interacting with the separation bubble. Further downstream, the tip vortices appear as rather diffuse regions in shades of yellow and green. The tip vortices appear to be drawing in flow from the separation wake at the further downstream stations. A rather curious effect was noted in taking data at the second survey station ($x/c = 0.43$) for the fully stalled wing. On the right side, it can be seen that the wake flow has a small region of distortion. In this area, the flow was apparently very unstable as observed by the wild excursion of the X-Y plotter being used as a monitor. Subtle shades of blue show the variation of speed and/or direction in the "freestream" flow about the wing. It is interesting to note that even the slight wake from the struts can be observed in the color shadings.



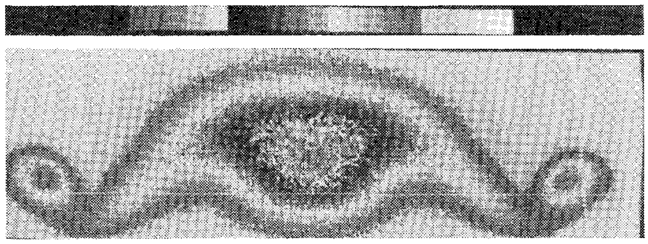
a) Hot-wire dc.

b) Hot-wire rms.

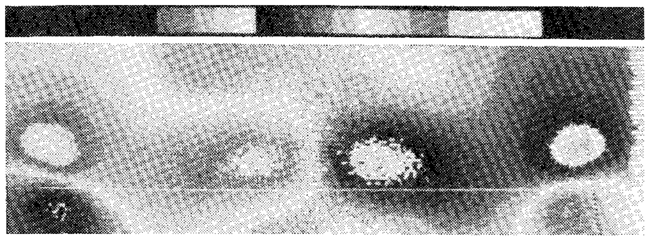


c) Split film.

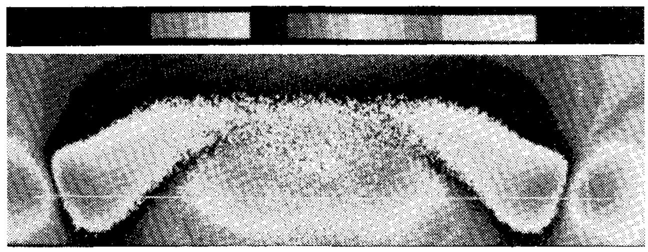
Fig. 7 Color video displays of chordwise surveys using a hot-wire probe and a split-film probe (centerplane of wing, $\alpha = 28.4$ deg). Color code runs from minimum on left to maximum on right.



a) Magnitude of velocity U (color code runs from 6.1 m/s on left to 54.9 m/s on right).



b) Yaw angle β (color code runs from -30 deg on left to $+30$ deg).



c) Pitch angle θ (color code runs from -30 deg on left to 30 deg).

Fig. 8 Color video displays of five-tube probe survey at $x/c = 2.70$, $\alpha = 28.4$ deg.

Figure 6 also shows the color video displays of the Conrad (pitch) probe measurements at $x/c = 2.70$. The tip vortex for the partially stalled wing causes very sharp color changes to occur. No evidence appears to exist in the data (at $\alpha = 21.4$ deg) of any vortex flow that may be streaming rearward from the swirl patterns noted in the oil flow pictures of Fig. 4. For the fully stalled wing, the tip vortices appear rather diffuse. The diffuse nature of the tip vortices may suggest that the vortices on the fully stalled wing have burst or are meandering around. It should be remembered that this type of data display is essentially a time-averaged picture of the flowfield.

The results of the chordwise hot-wire and split-film surveys are shown in Fig. 7. Twenty color levels were used in the data presentation to further increase the resolution. The hot-wire data (dc and rms levels) indicate a bubble-like separation region very similar to that seen in previous smoke flow tests on this wing.[5] It is interesting to note that the highest rms levels do occur (as one would expect) in the shear layer between the separated wake region and the surrounding freestream flow. The split-film data clearly show the apparent recirculating region seen repeatedly in the various flow visualization techniques used to explore the flowfield. The data appear to show intermittent flow reversal to at least $x/c = 3.0$. If the flow on the centerplane of the wing can be considered to be two-dimensional (i.e., flow in a plane with no cross flow), then the data shown in Fig. 7 can be interpreted in a more quantitative manner than the data in Fig. 6. However, because the flow is highly unsteady, the data in Fig. 7 are a rather smeared-out, long-term average picture of the wake flow. Advanced data processing techniques involving conditional sampling may help to resolve this problem in the future.

Preliminary results of a spanwise survey obtained with a scanning five-tube probe at the farthest downstream station ($x/c = 2.70$ and $\alpha = 28.4$ deg) are shown in Fig. 8. The data are presented as the magnitude of the local velocity U, the yaw angle β, and the pitch angle θ. The 20 color levels for U were divided into 2.4 m/s increments from 6.1 to 54.9 m/s. For both β and θ, a range of -30 to $+30$ deg was used, with each color being equal to a 3 deg window. The rather noticeable distortions on the left and right sides of the image display apparently were caused by a misadjustment of the PDP-11/Grinnell video system. In addition, a problem was encountered with spurious data points, which caused a data dropout at a number of points on the right side of the picture. The distribution of U appears very similar to the data obtained with the hot-wire probe at the same station (Fig. 6). For both probe surveys, the center region of the diffuse tip vortices indicated moderate to low values of U. The yaw angle β display indicates the correct trend of data at the wing tips, consistent with the flow created by the tip vortices. The pitch angle θ display is similar to the qualitative Conrad probe data shown in Fig. 6 and the trend of the color variations are consistent with the tip vortex flow.

Concluding Remarks

This paper has described the application of a new computer-driven color video display technique for use in the presentation of flowfield survey data. This technique allows one to present and interpret vast quantities of data that heretofore would have been difficult or impossible to comprehend. The use of the computer, together with high-resolution scanning, allows one to map out a flowfield in minute detail and display the data as a multicolored picture. The data displays can be qualitative, where relative color changes show the flowfield patterns, or quantitative, where each color represents a specific range of data such as pressure, magnitude of velocity, etc. The use of the video technique allows one to process and reprocess the data in any manner desired. Typical examples of this capability include magnification of a specific region of the data plane, variable scaling, image subtraction, and color reassignment.

In the current technique, the flowfield is scanned in an "*x-y*" fashion that results in a rectangular "sheet" of data. In wind tunnels where models are sting mounted, it may be more convenient to mount a traverse device on the sting and survey the flowfield in circular arcs (e.g., surveying the flowfield downstream of a cone model). Obviously, many different traverse designs can be used depending on the test geometry and the type of data desired. The choice of the traverse mechanism will have some effect on the subsequent data processing required. The "*x-y*" mechanism in Fig. 1 scans the data "sheet" in a manner similar to the way a video image is projected (scanned)—i.e., in the natural raster scan mode. Hence, each scan across the data plane with the probe will be displayed on the video screen as a single scan line. Taking data in this manner can simplify the data processing, since the computer deals with only one complete scan line at a time. On the other hand, if data were taken with a probe that surveyed in circular arcs, then each "scan" of the probe would cut across several video scan lines (since the video display is rectangular). In this case, some additional data processing and sorting would be required.

The time required to complete a high-resolution flowfield survey will depend on the speed of the traverse device, the time response of the probe, and the speed at which the data can be handled. The wake surveys completed for this paper required test runs of 1-3 h/station. Relatively slow scan rates were required for the heated element probes because of the slow conversion rate of the A/D system. Surveys using the pressure probes were slow because of the slow response of the probe/pressure transducer arrangements. More recent work at the University of Maryland, with a faster A/D system and a pitot probe with a pressure transducer embedded in the probe tip, allows complete wake surveys to be taken in about 10 min. The time to complete a flowfield survey could be reduced dramatically by scanning with a multiprobe rake. However, care must be exercised when using a probe rake to avoid flowfield interference effects.

The data taken for this report were not displayed until some hours after a test because of the rather involved and time-consuming job of processing the data through three different computer systems. With a self-contained data processing and color graphics display system, one could display the data in real time while the test is under way. This capability would have obvious advantages in tests of an exploratory nature.

Although a color graphics terminal may be able to display thousands of shades of colors, only a small fraction can be used for quantitative displays of experimental data—i.e., where one can point to a color in the data and find it on the color code chart. On the video monitor, this number (at most) is on the order of 30 colors. By the time the displays are photographed and copied (Xerox, etc.) for reports, this number is reduced to perhaps about 20. As noted earlier, the colors used for the data displays in this paper were selected solely on the basis of which combination seemed to give the most graphic and colorful displays. The colors were essentially arranged in the natural color spectrum (i.e., shades of red to shades of blue). In some cases, it may be appropriate to select a color code that helps one associate the data display with the conditions existing in the test. For example, in Ref. 6, red was used to indicate regions of high temperature and blue to indicate regions of cool temperatures in a thermocouple survey of a jet engine mixer nozzle. It has been suggested that colors such as red, which are associated with a "warning" or "alarm," should be used to code the specific data levels that are of particular interest (e.g., coding low-velocity separated flow regions in red such that they "stand out" in a data display).

The data presented in this paper were obtained in flowfield surveys behind a stationary wing model with a separated wake flow that is inherently unsteady. The data displays represent only a time-averaged "picture" of the flowfield. However, the video technique is not limited to surveys behind stationary models or to displaying only an average picture of an unsteady flowfield. In recent tests at the University of Maryland, data were taken downstream of a wing model that was oscillated in pitch between 10 and 20 deg at 7.5 Hz/s. Conditional sampling techniques were used to "extract" data "images" at select angles of attack from a vast data file generated during the test. The data displays clearly showed "instantaneous slices" of the cyclically changing flowfield.

The use of high-resolution video graphics terminals, film recorders, and three-dimensional (stereographic and holographic) display techniques will certainly open a new era in the presentation of flowfield survey data. Three-dimensional images of a flowfield could be constructed after one had taken multiple "slices" of data at different stations behind a model. Higher-resolution color video screens would allow one to use colored arrow heads to display the magnitude of velocity (as a color level) and the flow direction in a plane.

The use of the color video display technique poses a serious problem when the results are to be printed in a publication generally restricted to black-and-white reproduction. It has been suggested that one solution to this problem is to use clearly contrasted bands of a grey scale to display data for black-and-white publications. Hopefully, the cost of publishing in color will someday be low enough so that reports can provide the full impact of these truly beautiful color video displays.

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