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ADVANCED MEASUREMENT TECHNIQUES - PART I

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TRANSITION PHYSICS RESEARCH

In modern laminar flow flight and wind tunnel research, it is important to understand the specific cause(s) of laminar to turbulent boundary-layer transition. Such information is crucial to the exploration of the limits of practical application of laminar flow for drag reduction on aircraft. The process of transition involves both the possible modes of disturbance growth, and the environmental conditioning of the instabilities by free-stream or surface conditions (see fig. 1). The possible modes of disturbance growth include viscous (e.g. Tollmien-Schlichting), inviscid (e.g. crossflow), and modes which may bypass these "natural" ones. Theory provides information on the possible modes of disturbance amplification, but experiment must be relied upon to determine which of those modes actually dominates the transition process in a given environment. This presentation covers the results to date of research on advanced devices and methods used for the study of transition phenomena in the subsonic and transonic flight and wind tunnel environments.

Cause(s) of transition = [Mode(s) of disturbance growth] × [Environmentally conditioned instabilities]

Mode(s) of disturbance growth	Environmentally conditioned instabilities
Viscous	Turbulence
Inviscid	Vorticity
Bypasses	Thermal
	Acoustics
	Vibration

Figure 1

TRANSITION IN THE FLIGHT ENVIRONMENT

Different experimental environments can produce different transition modes. In the subsonic flight environment, the instabilities of practical interest include the Tollmien-Schlichting instability in two-dimensional boundary layers, laminar separation-induced inflectional instability, crossflow instability in three-dimensional boundary layers, and instabilities which may bypass these "natural" modes, caused by surface imperfections or acoustics for example (fig. 2). Very few flight transition experiments have attempted to document the mode of disturbance growth or cause of transition (ref. 1). The data published in nearly all past experiments focus on the transition locations without exploring the dominant instability(ies) responsible for initiating the transition process. Ultimately it is very important that transition studies be conducted at the speeds and altitudes at which the laminar-flow technology is intended to be applied. This is important because on laminar airframe surfaces which are practical to build and maintain, the transition process will be influenced by unit Reynolds number as well as length Reynolds number. The simultaneous scaling of both of these parameters is not possible; large-scale flight conditions are required for complete understanding of transition behavior.

- Tollmien-Schlichting instability
  - 2-D boundary layers/unswept wings
- Laminar separation
- Crossflow instability
  - 3-D boundary layers/swept wings
- Bypasses
  - Manufacturing tolerances
  - Engine/airframe noise
  - Insect contamination

Figure 2

TRANSITION MEASUREMENT TECHNIQUES

Laminar, transitional, and turbulent flows exhibit a variety of changes in fluid properties which provide the means to detect the state of the flow. Such property changes include skin friction, boundary-layer thickness, local turbulence, heat transfer, mass transfer, local flow direction, and others. Past research has made extensive use of a wide variety of transition measurement methods which rely on the flow properties mentioned. Such methods include sublimating chemical, oil flow, China clay, acoustic sensors, total surface tubes, liquid films, hot films sensors, and liquid crystals. Each technique has advantages and disadvantges. Hot films, for example, are extremely useful for continuous recording of point-measurements of transition during continuously changing test conditions. In the past, however, hot-film transition sensors were not widely used to detect the spatial or temporal mode behavior of the transition process (e.g. for laminar separation-induced transition behavior). Some of the available transition visualization methods such as sublimating chemicals have the advantage that they can provide for post-flight observations of transition details (ref 2). However, flow visualization of transition using sublimating chemicals was not practical at flight altitudes much above 20,000 feet. This presentation concentrates on recent research on arrayed hot-film sensors for use in transition mode measurements and on the development of the liquid-crystal method for flow visualization (fig. 3).

- Sublimating chemicals
- Oil flow
- China clay
- Hot films
- Acoustic detection
- Total pressure surface tubes
- Liquid film
- Liquid crystals

Figure 3

ARRAYED HOT-FILM DEVICES FOR MEASUREMENT OF TRANSITION LOCATION AND MODE

Applications of thin hot-film devices to measure transition location began in the early 1930's, and their use since then has been principally limited to single-point measurements of transition location. Thus, except for a few experiments where Tollmien-Schlichting wave frequencies were measured with hot-films, these devices have not been used to detect transition mode. Three arrayed hot-film device concepts have recently been developed for detection of transition modes, the multi-element hot-film transition sensor, the laminar separation bubble sensor, and the laminar crossflow vorticity sensor (ref 3). While these arrayed hot-film concepts can apply to either wind tunnel or flight research, the present discussion focuses on flight applications. For many flight research applications, through-the-surface types of sensor installation are not practical. For such situations, the mounting of the sensors and associated signal leads must be done on the exterior surface. The problems associated with surface-mounted sensors are addressed by these arrayed hot-film devices. The multi-element transition sensor and the laminar separation sensor were evaluated in flight. The laminar separation sensor has been evaluated in wind tunnel tests, and the prototype crossflow sensor has not been tested (fig. 4).

- Multi-element hot-film transition sensor
- Laminar separation bubble sensor
- Laminar crossflow vorticity sensor

Figure 4

GATES LEARJET MODEL 28/29 AIRCRAFT

The flight evaluations of the advanced measurement techniques discussed in this presentation were conducted on a NASA-operated Lear Model 28/29 business jet airplane used at Langley for viscous drag reduction flight research (see figure 5). The airplane provides a flight envelope including Mach numbers up to 0.805, maximum unit Reynolds numbers up to 2.65 million per foot, and maximum altitudes up to 51,000 feet. The wing on this airplane incorporates a non-production, modified airfoil section. Both the wing and the winglet on this airplane have very smooth surfaces on which to conduct laminar-flow research.

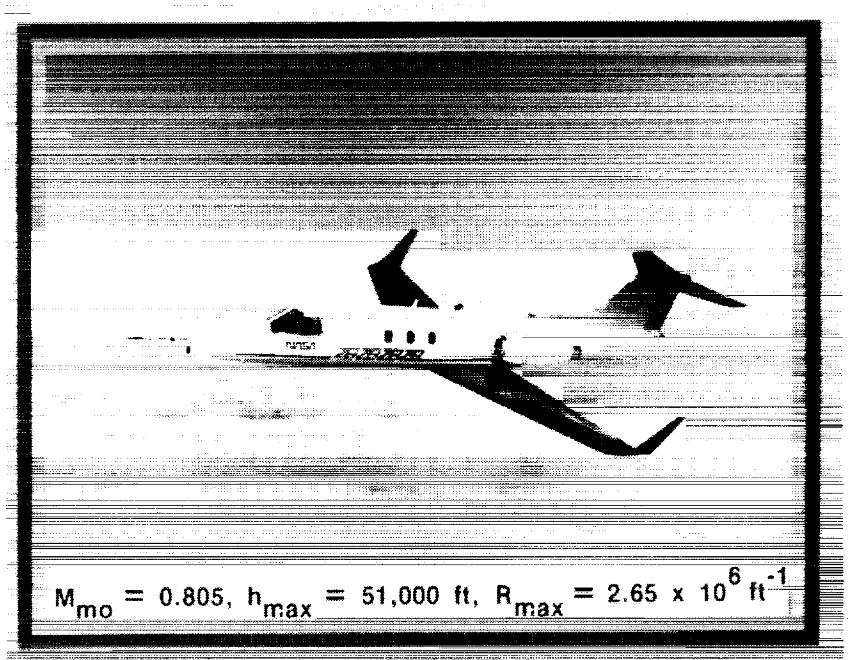


Figure 5

MULTI-ELEMENT HOT-FILM TRANSITION SENSOR

For many research efforts, it is important to study the growth of disturbances as nearly along streamlines as possible. Behavior along streamlines is of particular concern in three-dimensional flows, for example on swept wings and on three-dimensional bodies such as fuselages and engine nacelles. For these kinds of investigations, the multi-element hot-film sensor overcomes the disadvantages of the individual ("postage stamp") sensors often used in the past. The disadvantages of the individual surface-mounted hot-film sensors concern installation and signal interpretation. With individual hot-film sensors, downstream contamination of a sensor by an upstream neighboring sensor creates the requirement for staggering of the devices. This staggering of the sensors provides information on transition behavior along different streamwise stations for each sensor. In three-dimensional flows, staggering of the individual sensors may not provide useful transition behavior information. Other examples where the multi-element arrayed sensor may be useful include investigations of laminar-flow behavior in propeller slipstreams, during flight through clouds, or in the presence of acoustic disturbances where noise radiation patterns may not be uniform. The sensor is fabricated by imbedding the required number and spatial distribution of hot-film elements and signal leads between two layers of polyimide film. Figure 6 presents the geometric detail of a 25-element sensor design.

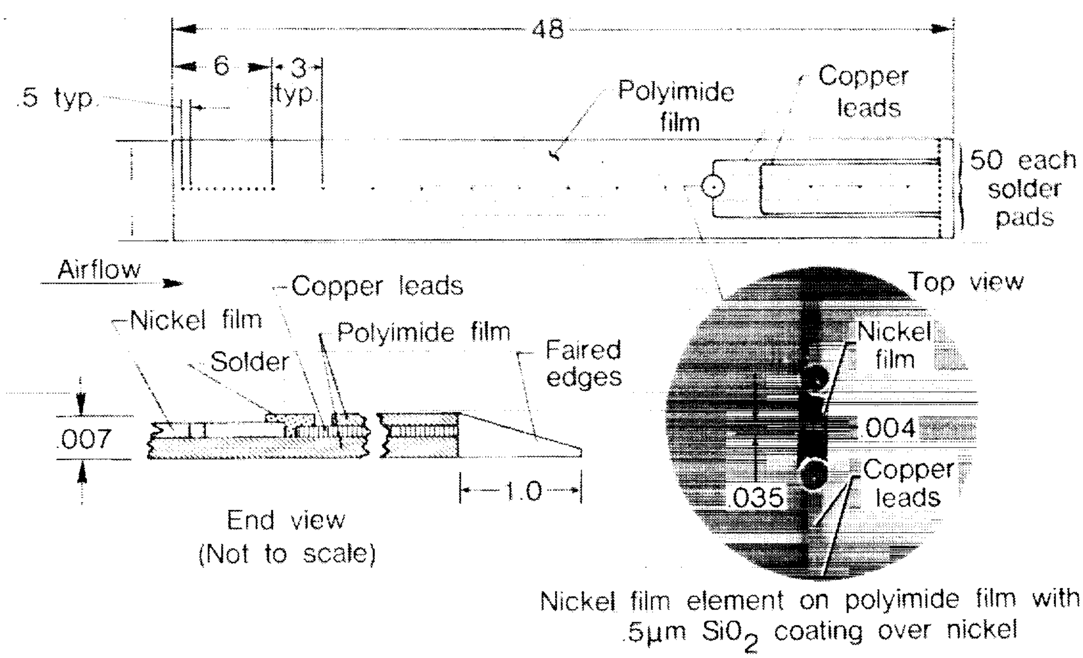


Figure 6

LEAR 28/29 HOT-FILM ANEMOMETRY INSTALLATION

Figure 7 depicts the arrangement of sensors on the left wing upper surface on the Lear 28/29. The figure shows the location of the multi-element sensor and the laminar separation sensors which were flown. Transition data acquisition with the multi-element sensor was accomplished using an electronic switching system which allows rapid switching of all sensor elements through six anemometers on board the airplane. Thus at any instant, six of the 25 sensor elements could be recorded simultaneously. Prior to operation of the multi-element sensor for transition investigation, the sensor and surrounding wing surface regions were sprayed with sublimating chemicals to ensure that the imperfect surface of the sensor did not cause transition. The results of these tests showed that for altitudes above about 29,000 feet where the cruise unit Reynolds number was below about 2.1 million per foot, the sensor roughness did not affect transition behavior.

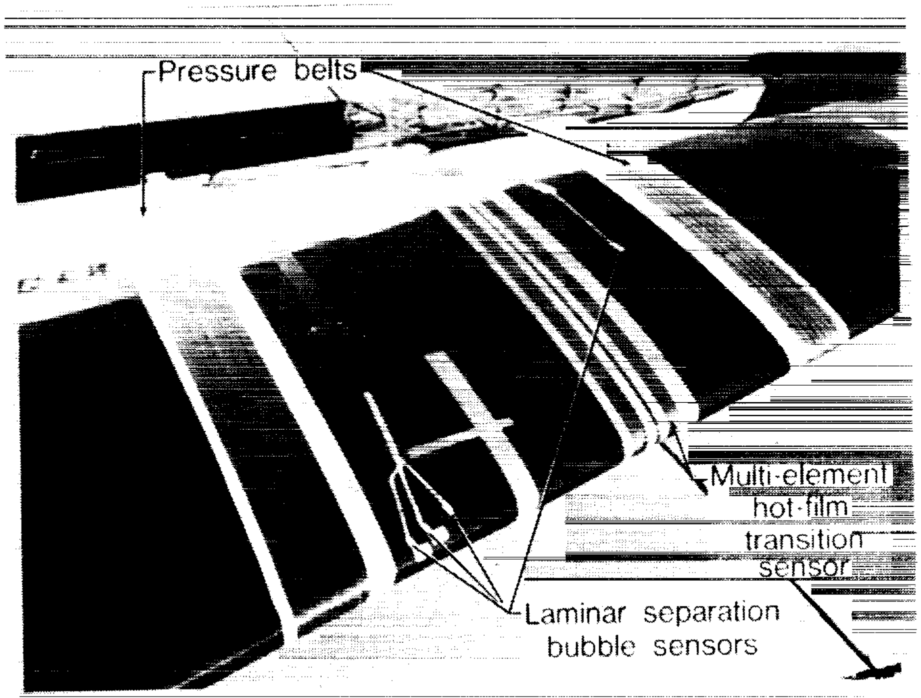


Figure 7

Figure 8a) illustrates typical transition data which can be acquired with the multi-element transition sensor; the pressure distribution (figure 8b) was measured with the pressure belts previously illustrated in figure 7. Transition onset is located at 41% chord where the first turbulent spikes are observed in the hot-film traces. The transitional boundary layer produces larger amplitude fluctuations in the signal traces, and at the end of the transitional region, the fully developed turbulent boundary layer produces the large amplitude uniformly fluctuating hot-film signal seen at the 52% chord element. The total length of the transition region extends over about eight percent of the chord. This transition region length and the character of the hot-film signal are indicative of Tollmien-Schlichting (T-S) initiated transition. To assure that this transition mechanism is active, analytical predictions of disturbance growth rates (n-factors) and most amplified T-S frequencies are compared to amplified hot-film signal data.

FLIGHT-MEASURED TRANSITION USING MULTI-ELEMENT SENSOR

M = 0.77, h_p = 39,000 ft, R_c = 8.8 x 106

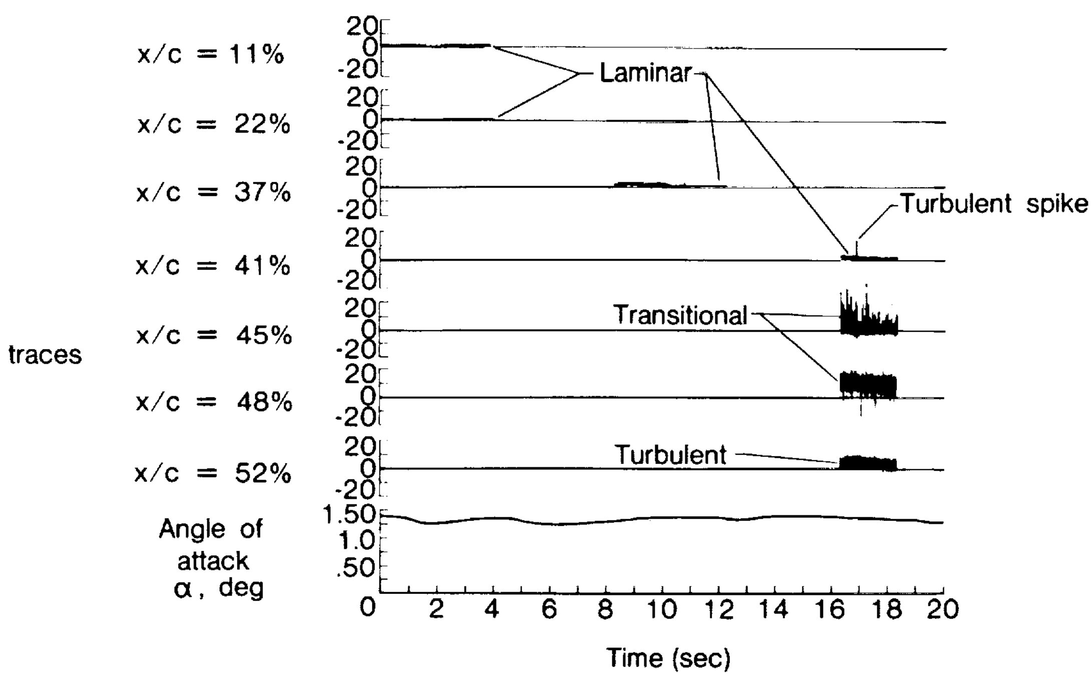


Figure 8a

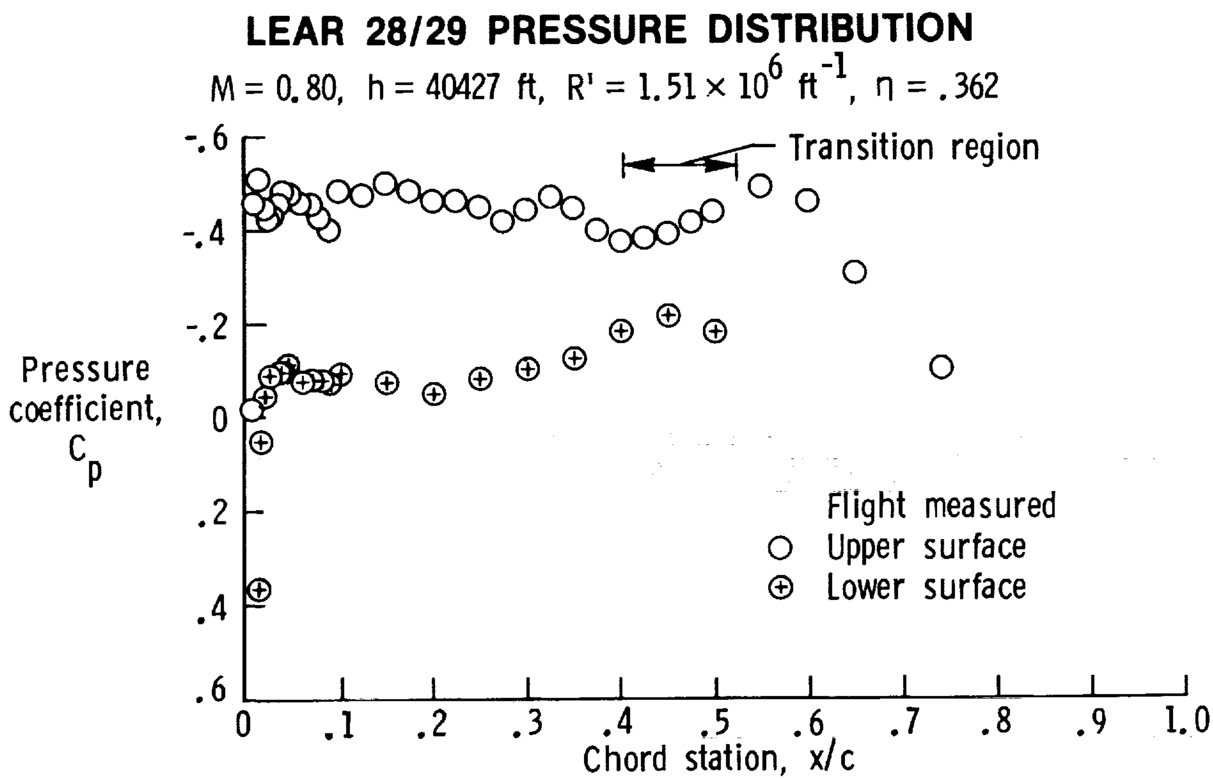

LEAR 28/29 PRESSURE DISTRIBUTION
M = 0.80, h = 40427 ft, R' = 1.51 × 10^6 ft^-1, η = .362
Transition region
Pressure coefficient, Cp
-.6
-.4
-.2
0
.2
.4
.6
0
.1
.2
.3
.4
.5
.6
.7
.8
.9
1.0
Chord station, x/c
Flight measured
Upper surface
Lower surface

Figure 8b

TOLLMIEN-SCHLICHTING INSTABILITY DETECTION FROM HOT-FILMS

The identification of the Tollmien-Schlichting disturbance frequencies associated with transition is important for validation of laminar stability theory, and for ruling out possible bypass-induced initiators of transition not related to "natural" T-S amplification. Figure 9 shows a hot-film signal trace from an individual hot-film sensor on the Lear 28/29 wing. With typical signal conditioning, hot-film records such as previously shown in figure 8 cannot be used to measure T-S frequencies; the hot-film signal must be amplified in order to detect these disturbances. The full-scale voltage of the laminar hot-film signal in figure 9 is of the same amplitude as the turbulent signals shown in figure 8. To provide the necessary sensitivity to detect T-S frequencies, the hot-film anemometry was operated with as large an overheat ratio as could be achieved without melting the sensor element, and the signal was given a high external gain prior to recording. Figure 9 shows 0.005 seconds of the data on an expanded time scale, revealing the periodic T-S oscillations. Spectral analysis of these signals can provide information on the most amplified frequencies for correlation with theory.

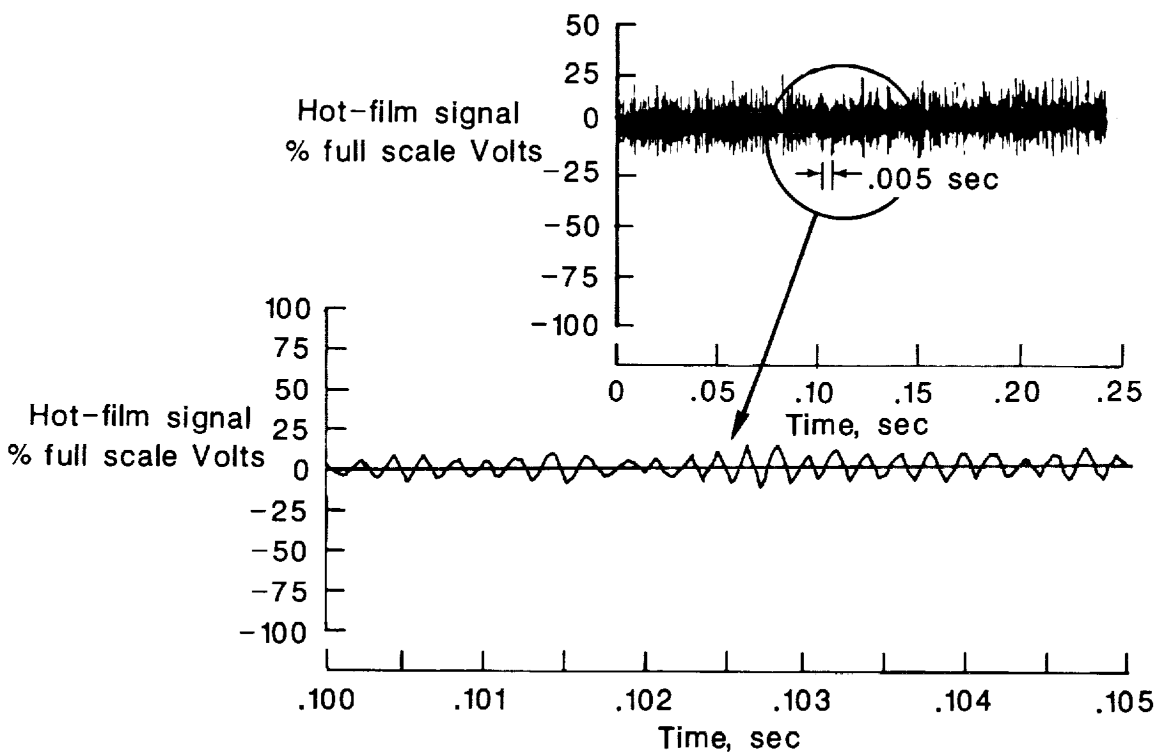


Figure 9

PREDICTED AND MEASURED TOLLMIEN-SCHLICHTING WAVE CHARACTERISTICS

The identification of the Tollmien-Schlichting frequencies associated with transition is important for validation of laminar stability theory and for ruling out possible bypass-induced initiators of transition not related to "natural" T-S amplification. Figure 10 illustrates the power spectral density (PSD) analysis of the T-S frequencies near transition measured in flight on the Lear 28/29 wing. The spectral analysis of the hot-film signal at transition onset shows that the most amplified frequencies occur near 4800 Hz. This frequency is in close agreement with theory. The hot-film spectrum can also show subharmonic or superharmonic frequencies, whereas the linear theory used only accounts for the growth of the fundamental frequency.

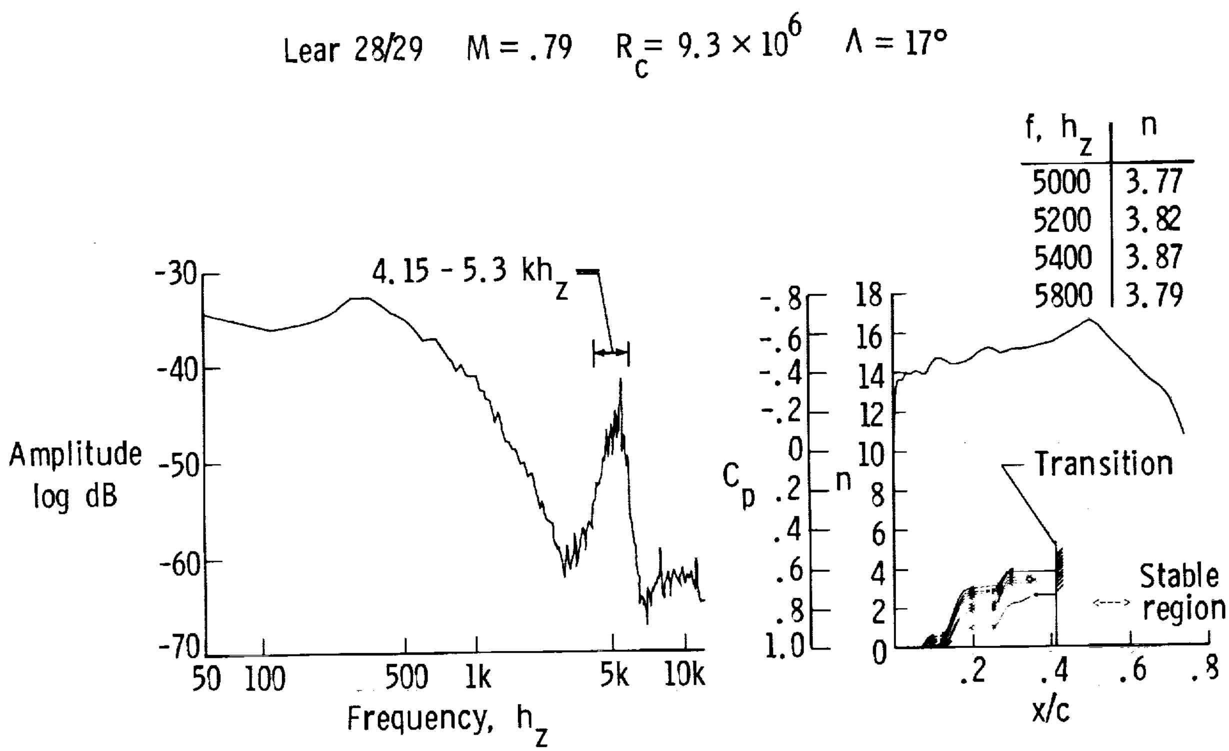


Figure 10

CONCEPTUAL OPERATING PRINCIPLE OF THE LAMINAR SEPARATION SENSOR

For many practical flight conditions of interest, boundary-layer transition may occur at the location of laminar separation, in a pressure recovery far downstream from the airfoil leading edge. This is most likely to occur in dominantly two-dimensional flows at moderate Reynolds numbers, but can occur in three-dimensional flows as well, for example on swept wings at lower Reynolds numbers. It is particularly important to identify the presence of laminar separation and the associated transition for calibration of laminar stability theory. Without such knowledge, it can be misleading to correlate predicted linear amplification ratios (n-factors) with experimental transition locations for the purpose of theory calibration for use in transition prediction. The laminar separation sensor conceptually illustrated in figure 11 provides a simple means for the detection of the presence of laminar separation and the associated transition. The sensor consists of an array of hot-films (three in the illustration) aligned in the direction of the local freestream. The center film is electronically heated by a constant temperature anemometer (CTA). The remaining two films, upstream and downstream of the center element, are incorporated into two legs of a bridge circuit to operate as resistance thermometers in a flow reversal meter (FRM) circuit. Thus, flow direction is detected when the heat from the center element is transported upstream or downstream.

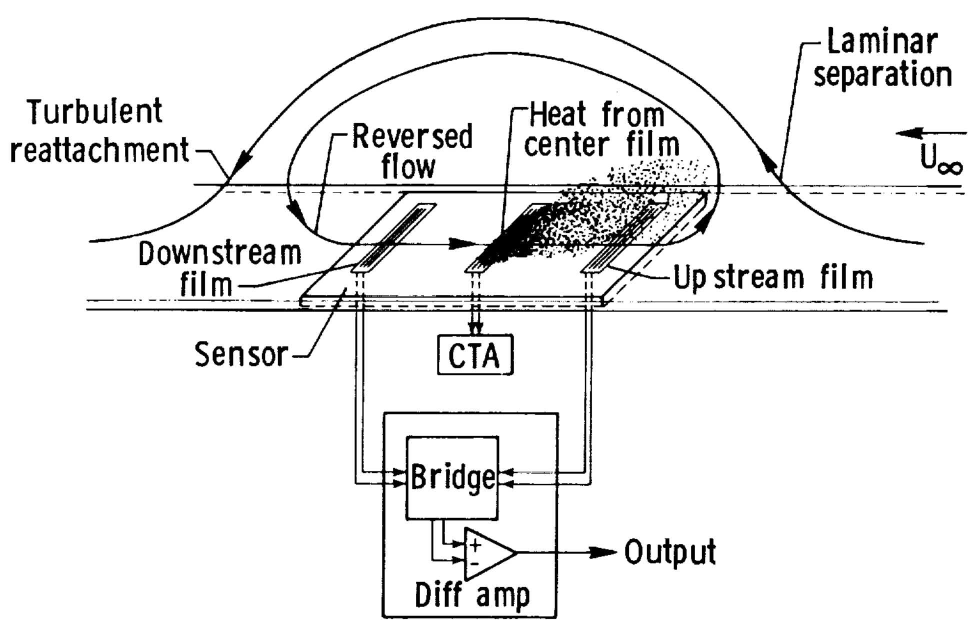


Figure 11

MULTI-ELEMENT LAMINAR SEPARATION ARRAYED HOT-FILM SENSOR

For detailed studies of laminar separation and transition behavior it is desirable to simultaneously measure the locations of separation of the laminar boundary-layer, transition on the bubble, and turbulent reattachment. These measurements have been accomplished using the array of hot-film elements shown in figure 12. With this configuration, the elements were operated in sets of three (sub-arrays) at a time. By switching the sub-arrays sequentially from the front of the sensor to the rear, the details of the laminar separation bubble can be measured.

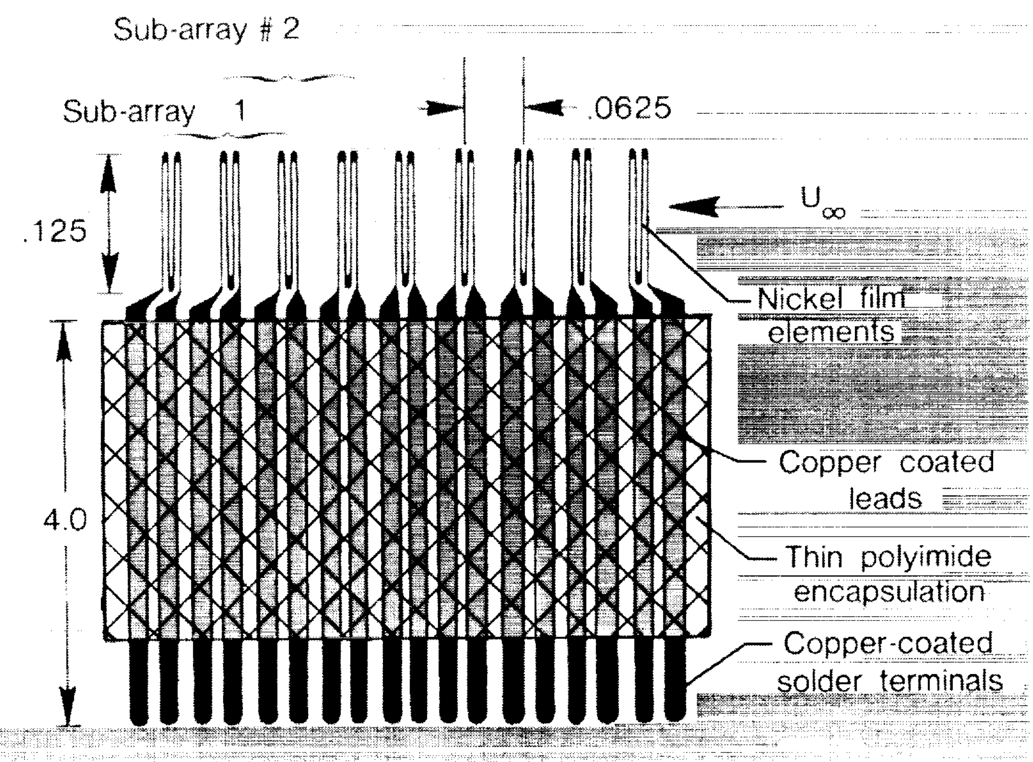


Figure 12

LAMINAR SEPARATION SENSOR WIND-TUNNEL EXPERIMENT

In figure 13, the experimental setup is shown of the laminar separation sensor installed on an airfoil model in the Langley 14x22-Foot Wind Tunnel. The arrangement includes the multi-element array with 48 elements at 1/16 inches spacing in the streamwise direction. The sensor is mounted on the upper surface of a 6-inch chord Wortmann airfoil. The model was designed and built at Notre Dame University for research on laminar bubble behavior planned by Dr. T. Mueller. This cooperative research effort also includes planned flight measurements of laminar bubble behavior on the same model to be conducted on a sailplane at Texas A&M University by Dr. S. Miley. The purpose of the Langley wind tunnel experiment shown in the figure was to evaluate the operation of the multi-element laminar separation bubble sensor prior to the planned flight experiments.

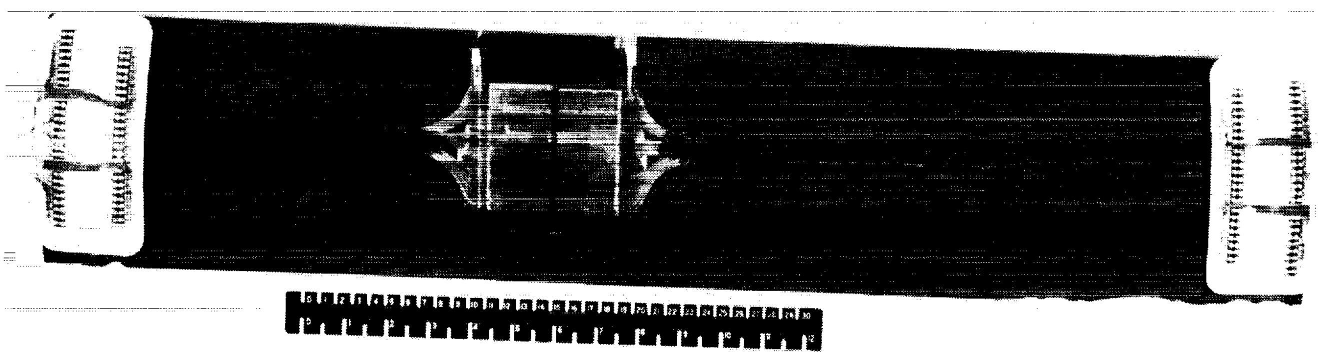


Figure 13

An example of transition and flow direction data from the laminar separation sensor is shown in figure 14. The figure presents oscillograph signals, both from the center elements (CTA's) of each sensor, and from the flow reversal meters (FRM's) monitoring the temperature differences between the outer two elements of each sensor. The data run began at a high angle of attack with transition occurring upstream of the forward-most sensor (no. 1). As shown in the figure, the center element in sensor no. 1 (CTA-1) indicated a turbulent boundary-layer state at the higher angle of attack, with transition moving across the element as angle of attack was reduced, until the element indicated a laminar state. The corresponding data from FRM-1 for this sensor showed that no flow reversal occurs. Thus, transition initiated by T-S amplification had occurred at location no. 1 for these conditions. The same data for sensor no. 3 (located in the middle of the bubble at zero degrees angle of attack) showed that this sensor experienced laminar separation. As angle of attack decreases, the passage of transition is indicated by CTA-2, and flow reversal is shown by the FRM-2 signals. The traces from CTA-2 behave differently from those on CTA-1. As transition moved across sensor no. 2, the CTA-2 signal shown in the figure changed from laminar to turbulent with a different behavior than was observed from CTA-1. The hot-film signal behavior on CTA-2 is typical of laminar-separation-induced transition signals.

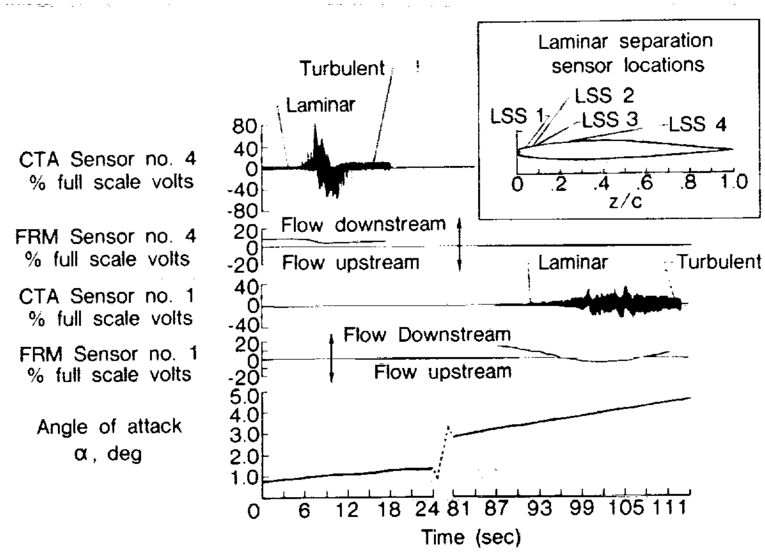


Figure 14

CONCEPTUAL OPERATING PRINCIPLE OF THE CROSSFLOW VORTICITY SENSOR

Near the leading edge of a swept wing, or on a body with non-axisymmetric pressure gradients, longitudinal vortices can develop in the laminar boundary layer, and can cause transition. Locally, these vortices cause spatial variations in heat transfer. As illustrated in figure 15, these variations in heat transfer can provide the source for detecting the wavelength (vortex spacing) and, if nonstationary, the most amplified frequencies of crossflow vorticity. A prototype crossflow vorticity sensor is illustrated in the figure. The spacing of the individual hot-film elements in the sensor is selected to provide accurate wavelength determination. Wind tunnel and flight experiments are planned to evaluate the performance of this sensor concept.

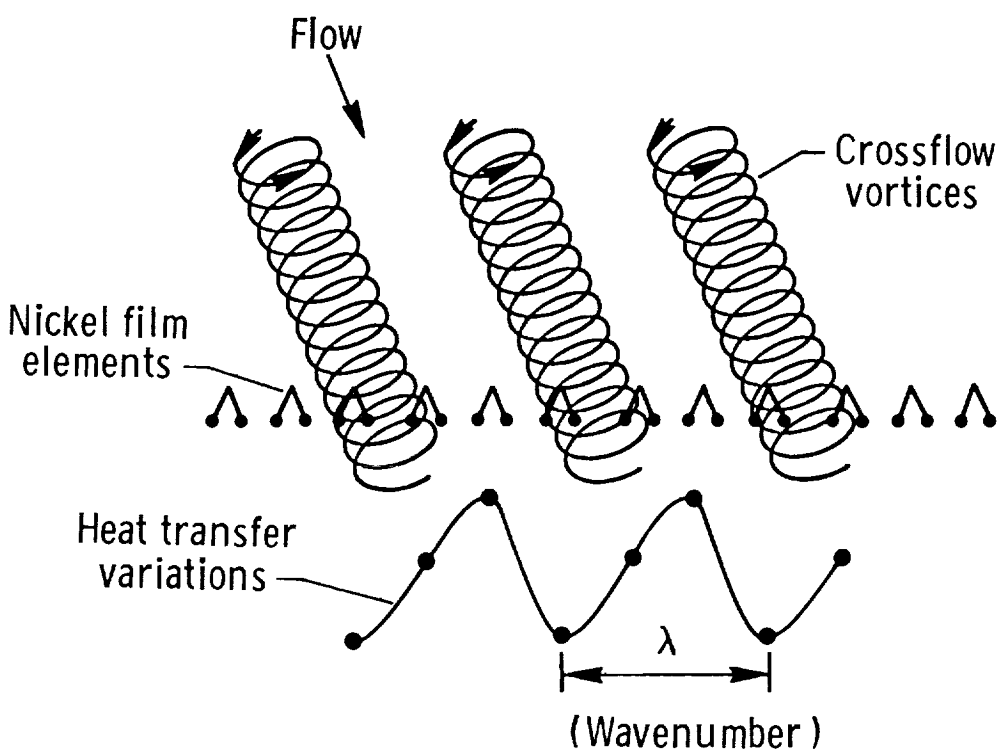


Figure 15

In the past, several methods for in-flight and for wind tunnel visualization of transition have been productively used. One most useful in recent work has been the sublimating chemical method, illustrated in figure 16. It has the advantage of providing, in many situations, data which can be recorded on the ground after the flight or after the wind tunnel is shut down. Unfortunately, sublimating chemicals have two significant disadvantages also. First, only one data point (transition measurement) can be obtained with a coating of chemicals; second, for altitudes above about 20,000 feet, sublimating chemicals or oil flows are impractical to use. For practical purposes, no means have been available in the past for transition visualization at the cruise altitudes of modern aircraft. Results will be presented here to illustrate the use of liquid crystals to overcome some of the shortcomings of prior means for transition visualization. (Fig 17.)

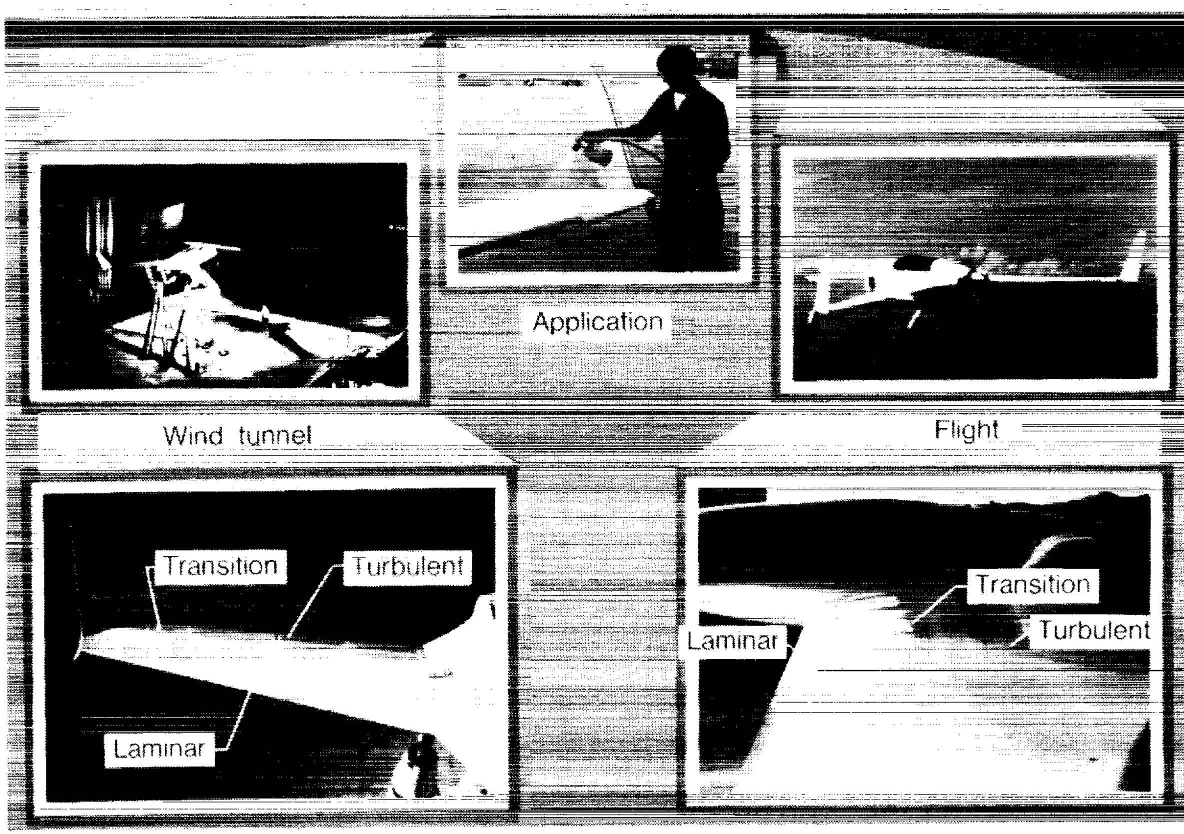


Figure 16

HOW LIQUID CRYSTALS INDICATE BOUNDARY-LAYER TRANSITION

Liquid crystals are a peculiar state of matter between solid and liquid. Although they appear as oily liquids, they have certain mechanical properties which are similiar to solid crystals. In particular, liquid crystals scatter light very selectively. Within a liquid crystal film, the axis of alignment of molecules is rotated in a helical fashion. The pitch length of the helix is within the range of visible light, and when subjected to certain physical influences, the helix pitch changes and the wavelength of the reflected light changes accordingly. In this fashion liquid crystal coatings change colors in response to changes in shear stress, temperature, pressure, ferromagnetism, and certain chemical vapors. References 4, 5, and 6 describe recent development and applications of the liquid crystal flow visualization method. (Fig 17.)

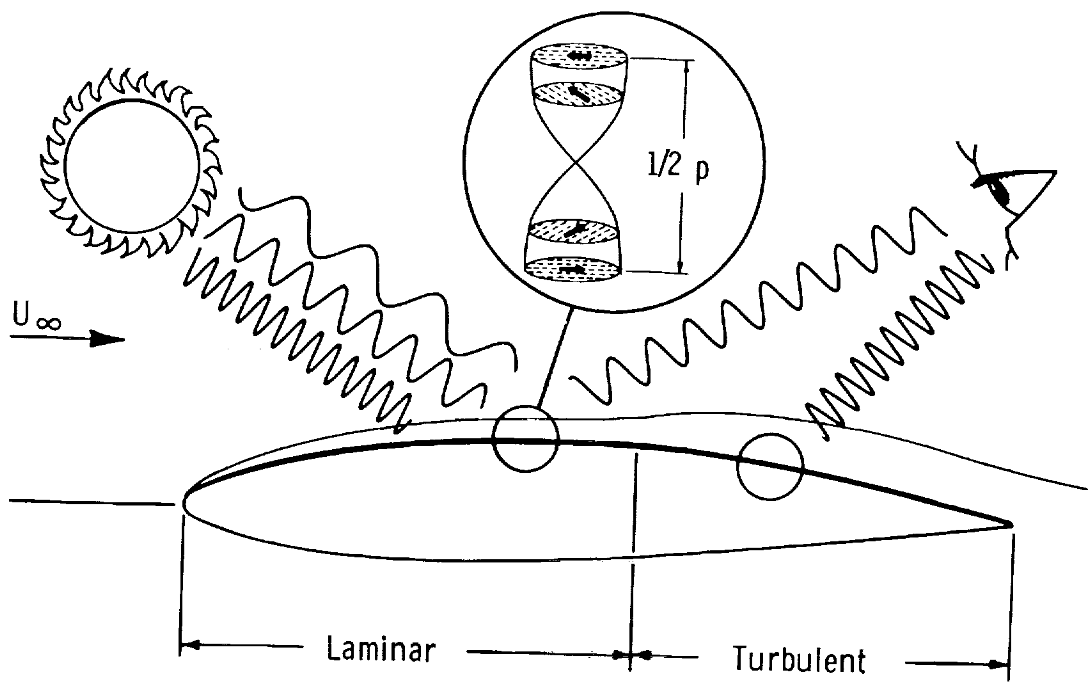


Figure 17

TRANSITION VISUALIZATION IN THE LEAR 28/29 WING USING LIQUID CRYSTALS

Exploratory flight experiments were conducted using many liquid crystal formulations on the wing and winglet of the Lear 28/29. Figure 18 shows the right wing of the airplane. The surface was prepared for testing by spraying on a deep matte flat black paint. A liquid crystal mixture is then formulated for the range of surface temperatures anticipated during the experiment. The mixture is formulated to have the color-play bandwidth (temperature range over which colors will appear) which will be most useful for the particular test needs. Narrower bandwidths (about 5 to 10 degrees Fahrenheit) have proven very useful for providing detailed resolution of transition location. Wider bandwidths (as much as 50 or more degrees Fahrenheit) have been useful for tests which experience wider temperature fluctuations. The liquid crystal material can be either brushed on neat, or thinned about 8 to 1 with solvent and sprayed on. By either technique, the objective is to obtain a very thin liquid crystal film. When applied with the proper film thickness, the liquid crystal coating will neither run, nor collect lint and other debris. The figure shows transition near the 30- to 35-percent chord location at Mach number of .8 at 48,000 feet. The regions of laminar flow appear blue in color, and no color appears in the turbulent areas; a few turbulent wedges appear emmanating from tape edges near the leading edge.

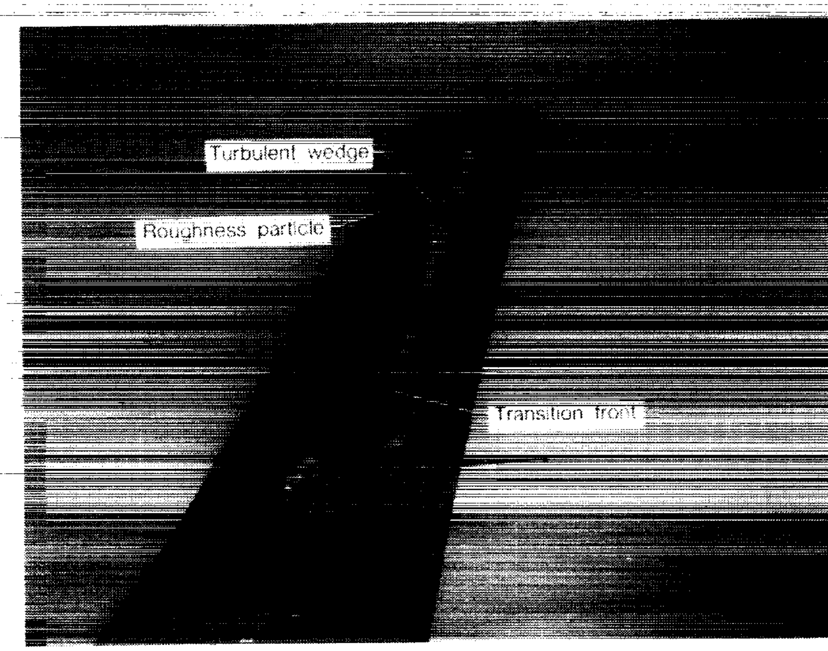
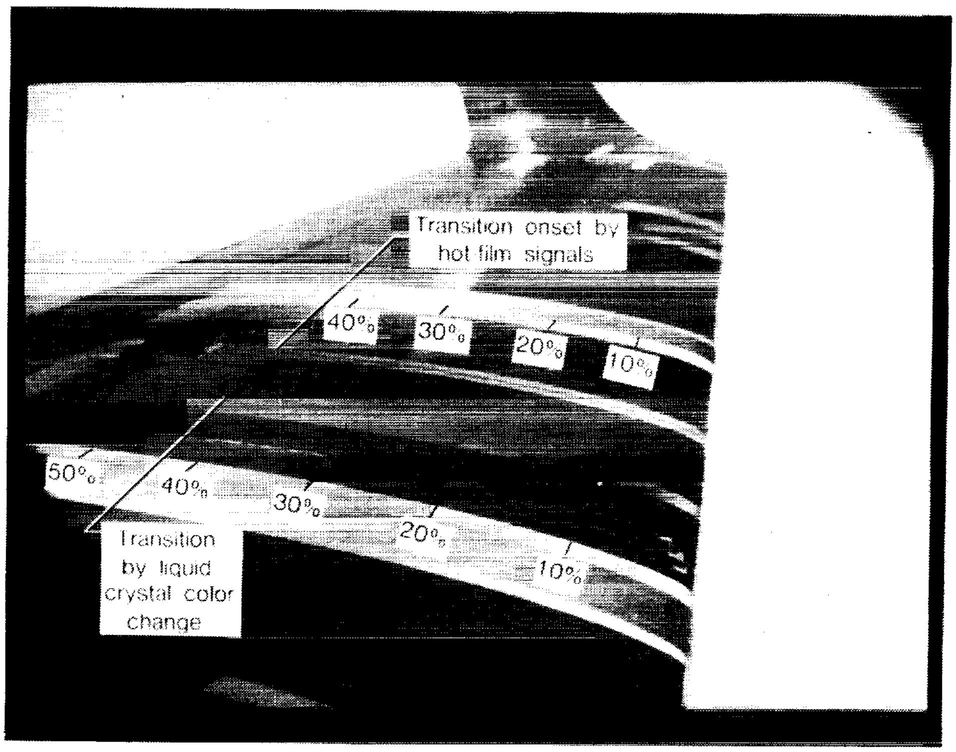


Figure 18

CORRELATION BETWEEN LIQUID CRYSTALS AND HOT-FILM TRANSITION INDICATIONS

In order to correlate the transition indications of the liquid crystals with another transition method, a liquid crystal coating was applied to the region on the left wing of the Learjet, where the multi-element hot-film sensor was installed. Figure 19 shows the transition as indicated by the liquid crystal coating at Mach = 0.8 at 48,000 feet. On-board real time observations of the hot-film signals on the oscilloscopes showed that the color change in the liquid crystal coating correlated with the first appearance of turbulent spots in the hot-films. Thus, with transition by Tollmien-Schlichting amplification,the liquid crystals show the onset of the transition region. This differs from the response of sublimating chemicals, which show the end of the transition region.



M = .8, h = 48,000 ft

Figure 19

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DYNAMIC RESPONSE OF LIQUID CRYSTAL COLOR CHANGES TO TRANSITION MOTION

An additional objective of the liquid crystal flight experiments on the Lear 28/29 was to qualitatively evaluate the time response of liquid crystal coatings to changes in transition location. Figure 20 shows elapsed time photographs taken from video record of the transition front motions on the winglet. Liquid crystals were brushed on the left winglet and flown at an altitude of 17,150 feet at Mach = 0.525. During this flight the airplane was oscillated to sideslip angles of +3.9 and -3.5 degrees with a period of 0.56 seconds. The resulting manuever provided variations in local angles of attack and pressure distributions on the winglet, causing transition to move from near the leading edge to near the 70 percent chord location. On this particular airfoil, pressure recovery at small angles of attack begins at about 65 percent chord. The observed movement of transition was in phase with the sideslip oscillation, indicating very rapid time response of the coating.

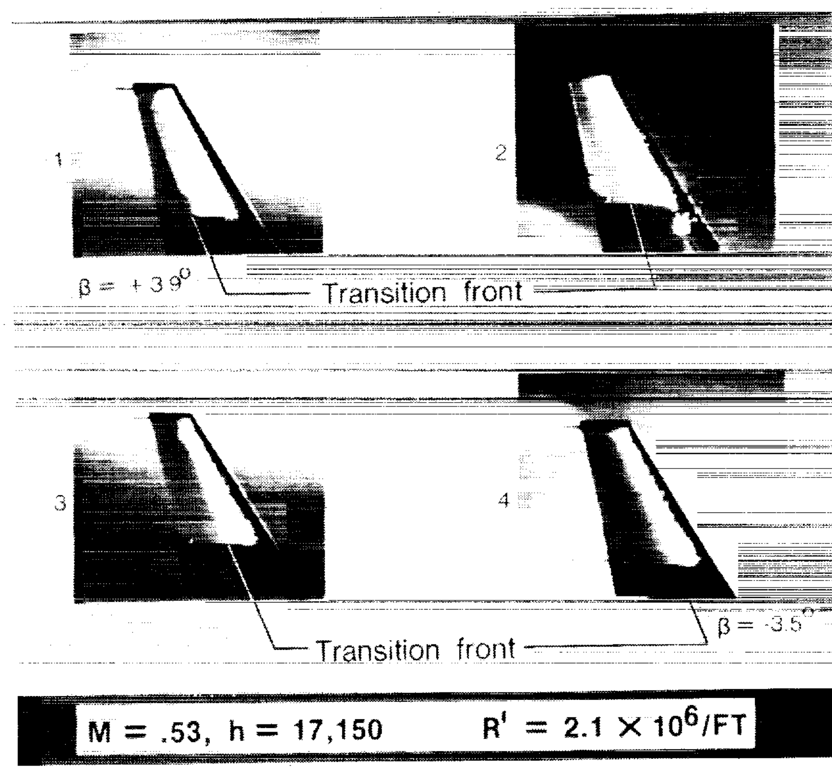

Figure 20

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The use of liquid crystal coatings in future transition research can provide data which is very difficult to acquire by other means. Such applications include the study of transition mode phenomena which are affected by changes in freestram disturbance states (e.g. acoustics) or by changes in geometry (e.g. sweep). The method overcomes one of the limitations of sublimating chemicals by providing continuous (reversible) indications of transition locations for flight conditions which are difficult to stabilize, such as at high angles of attack or sideslip. Liquid crystals have been used for visualization of shock and shock-induced separation in wind-tunnel testing, and for vizualization of transition in underwater testing (ref 7). Further evaluations are planned of encapsulated liquid crystal coatings which may be useful in applications where the thermal response to transition at compressible speeds may be sufficiently strong to provide needed information. Examples include tests on rotating surfaces (high-speed propellers) where the use of neat materials would not be practical. (Fig. 21.)

- Advantages
    - Reversible
    - Rapid time response
    - Non-toxic
    - Low cost
- Applications
    - Transient test conditions
    - Variable wing sweep
    - Variable acoustic disturbances
    - High altitudes

Figure 21

CONCLUDING REMARKS

Historically, as applications for laminar technology have been pushed to higher speeds, the necessary research tools have developed in parallel. With the progress in use of arrayed hot-film transition mode sensor technology and high-altitude liquid-crystal transition visualization methods, we see this trend in tool development continuing. Applications for laminar flow throughout future aircraft flight envelopes will require detailed knowledge of transition behavior. Transition mode behavior must be understood at the flight conditions of interest (i.e. real Mach numbers and altitudes) if passive and active laminar flow control applications are to be optimized.

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ADVANCED MEASUREMENT TECHNIQUES-PART II

INTRODUCTION

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In recent years a number of measurement techniques have been developed and refined for use in fluid mechanic flow diagnostics. These diagnostic tools have been primarily used in wind tunnels and, in several instances, have been extended for use in flight. The purpose of this paper is to present a brief review of some of the advanced techniques that have been developed by eight groups of researchers. The eight specific advanced techniques encompass five basic areas of measurements (fig. 1).

The first section describes the basic measurement of flow quality by a recently developed technique which uses a three-wire hot-wire probe to obtain velocity, density, and total temperature fluctuation in subsonic compressible flow. The three-wire-hot wire probe technique was primarily developed for use in the determination of wind tunnel disturbance levels, but, as indicated in this paper, it has also been used in flight (refs. 1, 2, 3, and 4).

The second section describes the basic type of measurement of boundary-layer transition detection by two somewhat different hot-film methods and by an optical method. The segment including the first hot-film method discusses the recent developments with a specialized hot-film system for on-line transition detection in cryogenic wind tunnels such as the U.S. National Transonic Facility (refs. 4, 5, 6, 7, 8, and 9). The segment describing the second hot-film technique discusses the measurement and theoretical validation of the existence of Tollmien-Schlichting waves that were obtained with a different hot-film system (ref. 10). The third transition detection technique discussed involves a recently developed nonintrusive optical system which uses a high-resolution interferometer coupled with electronic data acquisition system that senses changes in density fluctuation in the boundary layer to indicate the transition region (ref. 11).

The third type of basic measurement encompasses the general area of flow diagnostics (i.e., flow quality) made with two types of three component laser velocimeter (LV) systems. The first LV system discussed is a single-axis five-beam system which indicates excellent resolution with the longitudinal and vertical (u and v) components of velocity but poor resolution with the spanwise component (w) of velocity due to a high degree of nonorthogonality between the laser beam and w component of velocity (refs. 12, 13, and 14). The second LV system discussed utilizes three orthogonal beams (and fringe patterns) for use in a "Basic Aerodynamic Research Facility" (ref. 15) which has test section side walls and ceiling made of glass to accommodate the "orthogonal LV" technique.

The fourth type of basic measurement is skin friction. This section describes a unique moving belt balance which was developed for the direct measurement of the wall shear stress (refs. 16, 17, and 18). Measurements with the moving belt balance made on the test section side walls of the two Langley facilities are presented.

The fifth basic type of measurement is flow visualization as applied to cryogenic wind tunnels. This section describes various background shadowgraph measurements made at different pressures and temperatures in a cryogenic tunnel (ref. 19). The modifications to the "test section optical access" that were required for an interference free background shadowgraph are discussed.

BASIC AREAS OF MEASUREMENTS

- Flow quality: three-wire hot-wire probe
- Transition detection: two hot-film techniques and an optical technique
- Flow diagnostics: two LV systems
- Skin friction measurements: moving belt balance
- Flow visualization: shadowgraphs in cryogenic tunnels

Figure 1