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RESEARCH MEMORANDUM

AIR-FLOW BEHAVIOR OVER THE WING OF AN XP-51 AIRPLANE AS
INDICATED BY WING-SURFACE TUFTS AT SUBCRITICAL
AND SUPERCRITICAL SPEEDS

By

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SUMMARY

Results are presented in this report of the air-flow behavior over the wing of an XP-51 airplane including photographs of tufts attached to the wing surface and chordwise pressure distributions. A comparison of tuft studies is made of the flight results with those obtained from wind-tunnel tests.

The results indicate that steady flow is obtained over the wing until the critical speed has been exceeded by about 0.04 to 0.05 in Mach number. At higher Mach numbers the flow is unsteady and becomes very rough and turbulent over the rear 50 percent of the chord after the limit maximum pressure coefficient has been reached. Observation of surface tufts alone without benefit of prevailing pressure distributions may indicate separated flow before separation actually occurs. Comparisons made of the flight and wind-tunnel data show a similar tuft behavior throughout the Mach number range.

INTRODUCTION

In connection with the evaluation of aerodynamic data obtained at supercritical speeds, the Air Materiel Command, Army Air Forces, requested information on the flow conditions over the wing of the P-51 airplane as would be indicated by wool tufts attached to the wing surface.

In addition to supplying substantiating aerodynamic data on supercritical flow phenomena it was felt that tuft pictures might assist in explaining speed limitations at the lift coefficients necessary for high-altitude operations as well as provide additional

data to assist in determining optimum wing loading and airfoil section selection to be used on development airplanes. A similar investigation has been conducted for the wing of the P-47D airplane and the results are presented in reference 1.

The data presented herein were obtained during dives of the XP-51 airplane for a Mach number range of 0.55 to 0.78 and a lift coefficient range of 0.10 to 0.90.

APPARATUS AND TESTS

The airplane used for the tests is shown in figure 1. The wing used on the XP-51 airplane is similar to that used on all production models of the fighter and incorporates a North American modified NACA 44-series airfoil section.

Wool tufts were attached to the upper surface of the left wing between the 46-inch station and the 150-inch station and chordwise pressure distribution was obtained at the 52-inch station (A) and the 114-inch station (B). (See fig. 2.) The area between these two stations is considered the test panel and has a chord length and maximum thickness of 91.0 inches and 0.153c, respectively, at station (A) and 75.3 inches and 0.141c, respectively, at station (B).

Photographs of the wool tufts during the tests were made by a 35-millimeter movie camera operating at a speed of approximately 48 frames per second. Simultaneous measurements of airspeed, altitude, normal acceleration, and wing surface pressures were made by standard NACA recording instruments.

The flight tests covered a range of airplane lift coefficients by making pull-ups from level flight at the lower Mach numbers and by making recoveries from dives at the higher Mach numbers. All data were obtained at approximately 20,000 feet.

RESULTS

Photographs of the tuft behavior during flight for various values of airplane lift coefficient at Mach numbers from 0.55 to 0.78 are presented in figures 3 and 4. The field of view is sufficient to include both pressure measuring stations A and B and a considerable portion of the 50-percent chord line. The photographs presented in figure 3 are arranged to show the tuft behavior at several Mach numbers for various airplane lift coefficients. Those presented

in figure 4 are arranged to show the tuft behavior at several lift coefficients for various Mach numbers.

The chordwise pressure distributions occurring at stations A and B for an airplane lift coefficient of 0.2 at various Mach numbers are presented in figure 5. More pressure points were available for establishing the distributions at station B than were available at A which may account for the greater irregularities shown at B since a more detailed fairing is possible. The critical pressure line (local $M = 1.0$) for the prevailing free-stream Mach number is superimposed on the pressure diagrams.

The types of flow, indicated by motion pictures from which figures 3 and 4 have been taken, have been classified into three general types:

(1) Steady flow - The tufts are, in general, directed toward the rear and are motionless with the exception of very small oscillations of the tuft ends.

(2) Unsteady flow - Tufts oscillating through a range of about 45° from the chord direction.

(3) Break-away flow - Tufts oscillating wildly about in all directions such as pointing forward, and being raised about 45° off of the surface. It may be mentioned here that the interpretations made of the tuft behavior in terms of existing flows in these tests differ somewhat from those made in reference 1; however, since interpretation of flows by use of tuft studies alone are necessarily qualitative, it is possible that differences in interpretation may exist.

Shown in figure 6 are boundaries of limit Mach numbers as a function of airplane lift coefficient. The boundaries have been established for (1) conditions of steady, unsteady, and break-away flow over the test panel (2) limit pressure coefficient and limit section normal-force coefficient occurring at station B and (3) the critical (local $M = 1.0$) at stations A and B. Limit pressure coefficient and limit normal-force coefficient as used herein are defined as the points at which the maximum pressure coefficient and the section normal-force coefficient cease to increase with an increase in Mach number for a given airplane lift coefficient. The actual Mach number and lift coefficient combinations used to establish the boundaries of flow conditions were determined from observations of the movie film showing the tuft behavior throughout the dive during each run. The results of the observations plotted in figure 6 may be used in combination with the photographs of figures 3 to 4 to obtain a visual concept of the air-flow behavior. Also included in figure 6 are curves of airplane lift coefficient required for level flight at altitudes of 20,000, 30,000, 40,000 and 50,000 feet for a wing loading of 33 pounds per square foot.

Figure 7 shows some comparisons obtained from the flight tuft measurements with those obtained during a survey made in the Ames 16-foot high-speed tunnel on the upper surface of the wing of a $\frac{1}{3}$ -scale model of the P-51B.

DISCUSSION

It may be noted in figure 3 that at Mach numbers of 0.55 and 0.65 for the lower lift coefficients the tufts indicate steady flow over the test panel but at the higher lift coefficients unsteady flow occurs over the flap. At a Mach number of 0.73 and a C_L of 0.20 the tufts at about 0.55c show a local state of unsteady flow and as the lift coefficient is increased the tufts from midchord location back to the trailing edge are unsteady. At Mach numbers higher than 0.73 unsteady and break-away flow aft of 0.55c is indicated by the tufts for all lift coefficients tested.

It may be seen from figure 6 that steady flow is maintained over the wing at Mach numbers less than 0.73 at a C_L of 0.10 and Mach numbers less than 0.68 at a C_L of 0.6, and that a linear relationship exists between these two limits to establish the boundary between steady and unsteady flow. It also may be seen from the critical pressure lines for stations A and B in figure 6 that the presence of unsteady flow occurs roughly 0.04 to 0.05 in Mach number after the critical of the test panel has been exceeded. At Mach numbers higher than 0.77 at a C_L of 0.10, or of Mach numbers higher than $M = 0.72$ at a C_L of 0.60 the flow becomes very rough and turbulent, so much so that a sudden change from unsteady to break-away flow is indicated by the motion pictures. The condition of unsteady flow over the wing changes to break-away flow shortly after the limit maximum pressure has been attained at station B. The limit section normal-force coefficient at station B occurs about 0.03 in Mach number after break-away flow is observed.

The behavior of the tufts indicates that the actual criticals can be exceeded somewhat before any change in flow pattern occurs to produce changes of the aerodynamic forces. The first indication of flow disturbance is local, representing only a small portion of the wing, but as the Mach number is increased further the disturbance takes place over 50 percent of the wing area.

The curves of airplane lift coefficient required for level flight at various altitudes included in figure 6 show that unsteady and break-away flow will occur over the wing about 0.03 in Mach number earlier at an altitude of 50,000 feet than at 20,000 feet.

From the chordwise pressure distributions presented in figure 5 it may be seen that the test panel is operating at supercritical speeds at Mach numbers above 0.65 for an airplane lift coefficient of 0.20. Pressure peaks occur at 50 to 55 percent of the chord which is the location at which unsteady flow was first observed over the wing. It may be noted that the pressure distributions do not indicate separation of flow over the panel since a normal pressure recovery is shown to occur after the peak pressure is reached. An analysis of the air-flow behavior by observations of surface tufts alone may erroneously indicate early stages of separated flow however, the additional information pertaining to existing pressure distributions show that separation has not yet occurred.

The comparisons between the tuft surveys made in the Ames 16-foot wind tunnel on a $\frac{1}{3}$ -scale model and the surveys made in flight show, in general, a similar tuft behavior. However, the flight tests showed unsteady flow over the landing flap at low Mach numbers and high lift coefficients which was possibly due to the landing-flap junction. At a Mach number of 0.75 and at a C_L of approximately 0.1 both tests show the flow is becoming unsteady behind the 50-percent chord point and at C_L of 0.3 both sets of data indicate greater turbulence is present over the entire rear half of the wing.

A comparison of the flight photographs for $M = 0.78$ and $C_L = 0.1$ with the wind-tunnel photographs for $M = 0.79$ and $C_L = 0.04$ shows that both tests indicate break-away flow over the rear of the wing starting at about 0.55c.

CONCLUSIONS

It may be concluded from studies of the air-flow behavior over the upper wing surface of a P-51 wing as indicated by surface tufts that:

1. Steady flow is maintained over the wing at a Mach number less than 0.73 for a C_L of 0.10 and a Mach number less than 0.68 for a C_L of 0.60; combinations of M and C_L higher than the linear relation between these values produce unsteady flows over the rear 50 percent of the wing surface. Unsteady flows are first observed roughly 0.04 to 0.05 in Mach number above the wing critical.

2. Break-away flow first occurs after Mach numbers of 0.77 and 0.72 at a C_L of 0.1 and 0.6, respectively, have been exceeded and is observed shortly after the limit maximum pressure coefficient has been reached. Limit normal-force coefficient of the wing section occurs about 0.03 in Mach number after break-away flow is first observed over the wing.

3. Observations of surface tufts alone without benefit of prevailing pressure distributions may indicate separated flow before separation actually occurs.

4. Surveys made in the wind tunnel and during flight showed good agreement with the exception of the flows occurring over the airplane landing flap. This discrepancy is probably due to the break in the wing surface at the flap junction.

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REFERENCE

1. Wood, Clotsire, and Zalovecik, John A.: Flight Investigation at High Speeds of Flow Conditions over an Airplane Wing as Indicated by Surface Tufts. NACA CB No. L5E22, 1945.

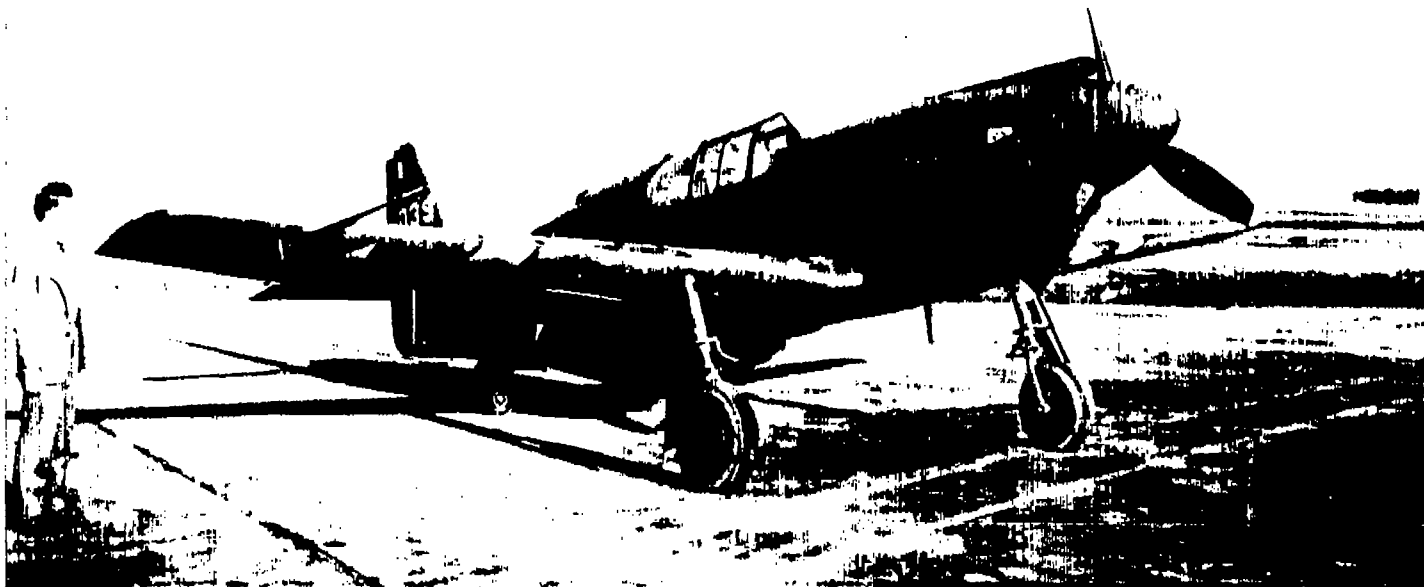
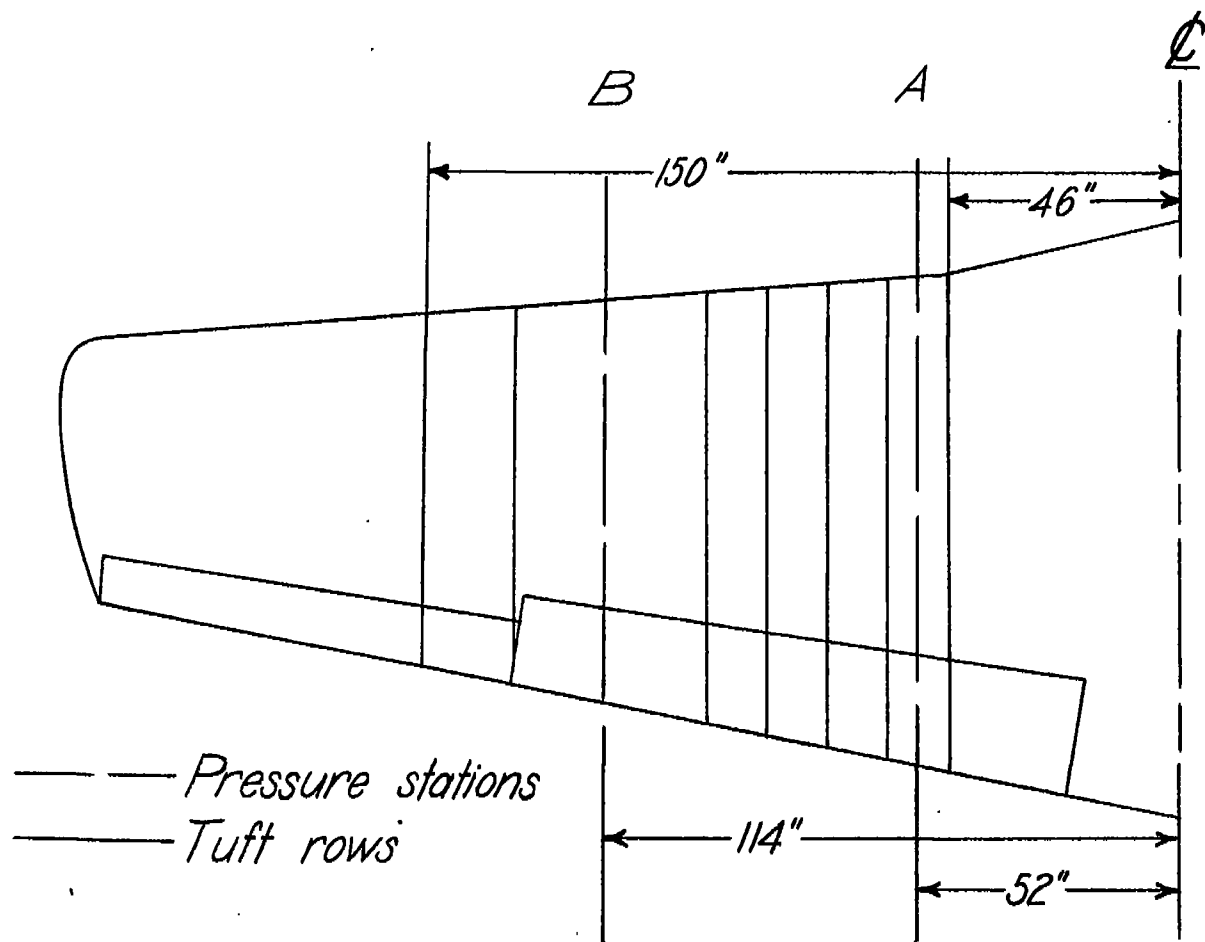
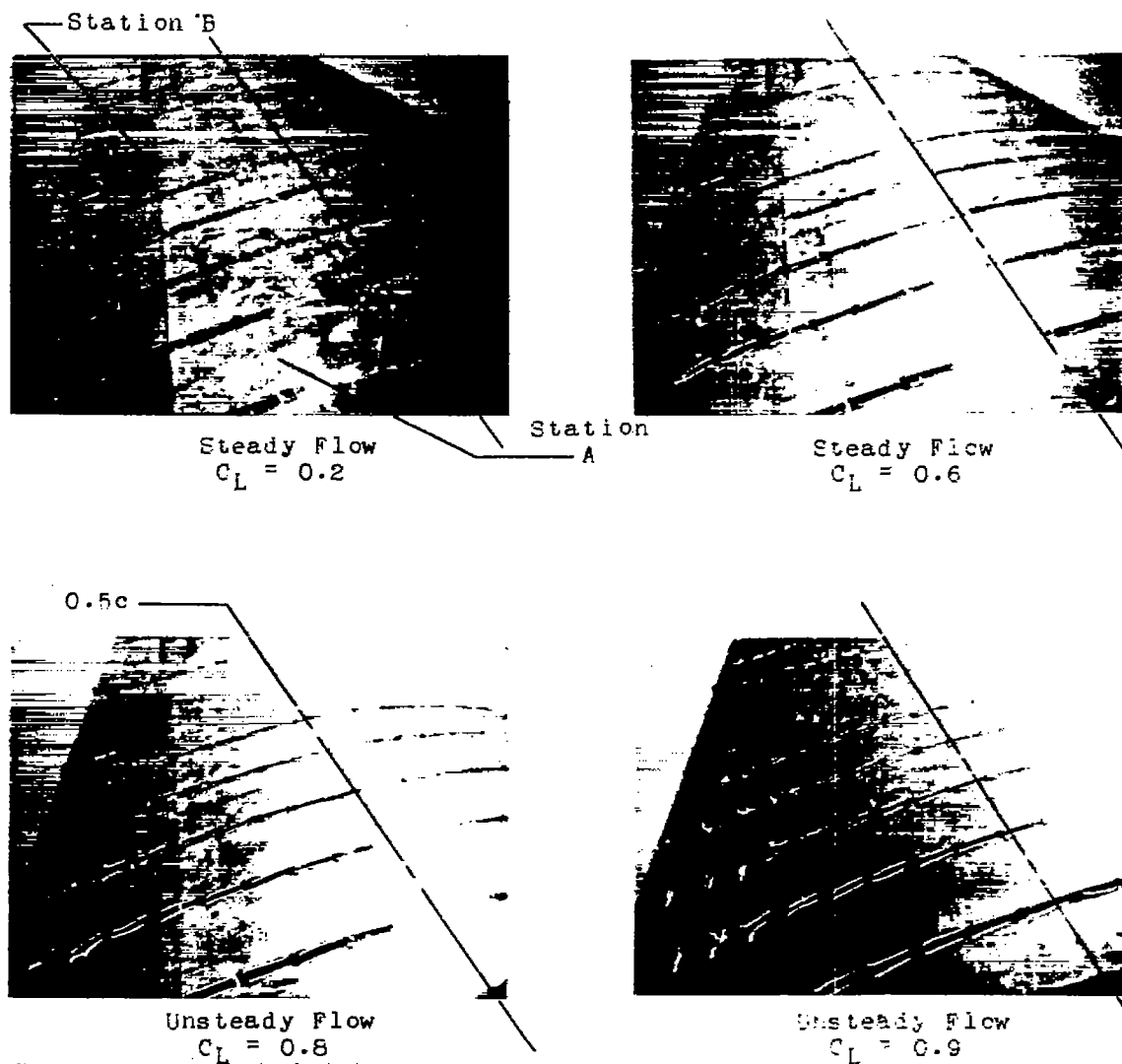


Figure 1.- Three-quarter front view of the XP-51 airplane.



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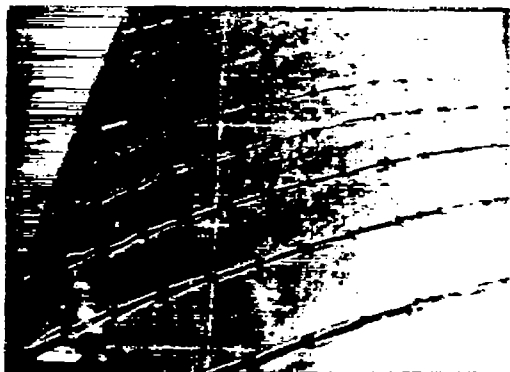
Figure 2.- Location of the tuft rows and pressure-measuring stations on the left wing of the XP-51 airplane.



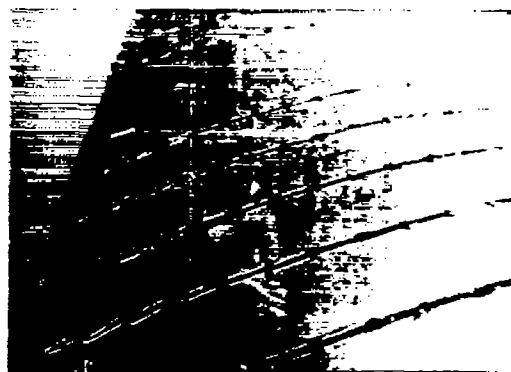
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(a) $M = 0.55$

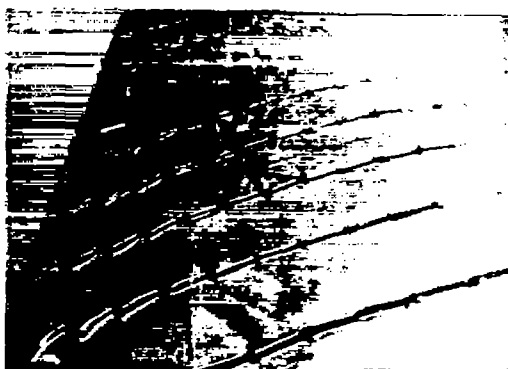
Figure 3.- Photographs of tuft behavior on the upper surface of the XP-51 wing at various airplane lift coefficients.



Steady Flow
 $C_L = 0.2$



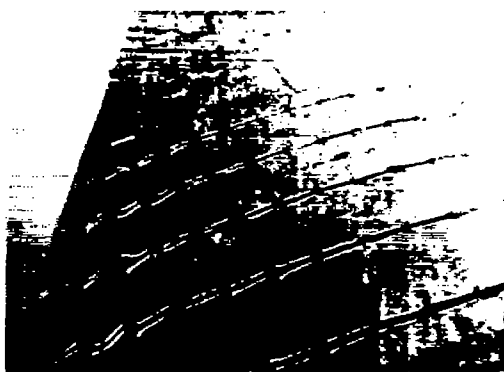
Steady Flow
 $C_L = 0.3$



Steady Flow
 $C_L = 0.4$



Steady Flow
 $C_L = 0.5$

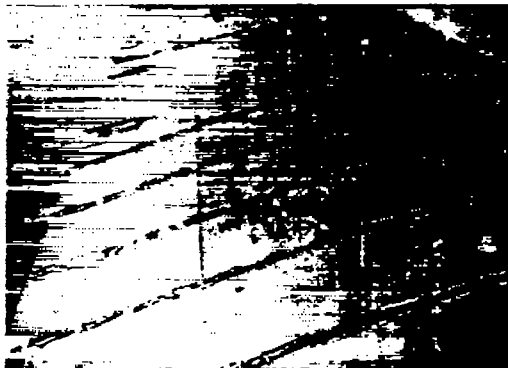


Unsteady Flow
 $C_L = 0.6$

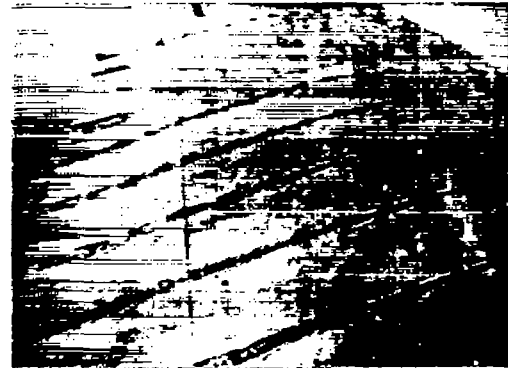
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(b) $M = 0.65$

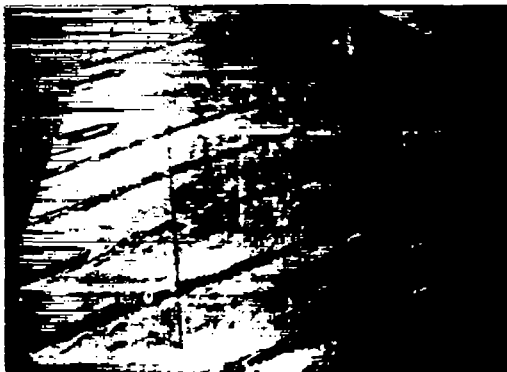
Figure 3.- Continued.



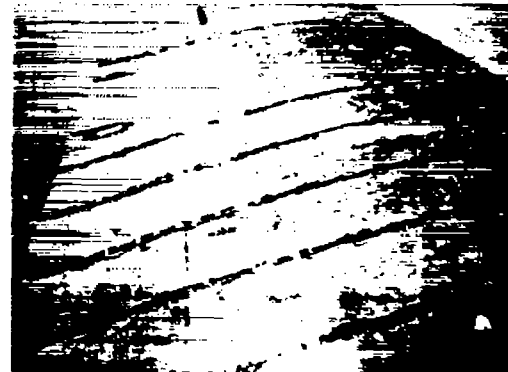
Steady Flow
 $C_L = 0.1$



Steady Flow
 $C_L = 0.2$



Steady Flow
 $C_L = 0.3$



Unsteady Flow
 $C_L = 0.4$

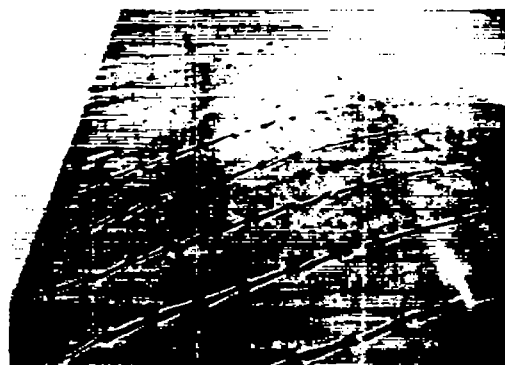
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(c) $M = 0.70$

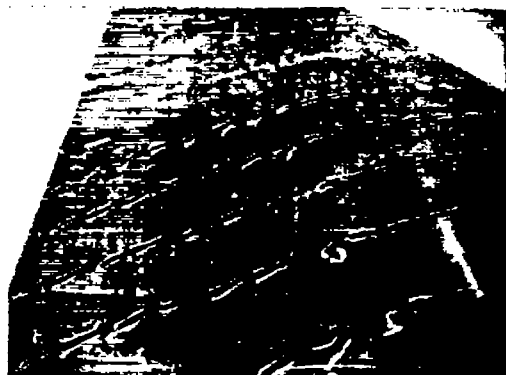
Figure 3.- Continued.



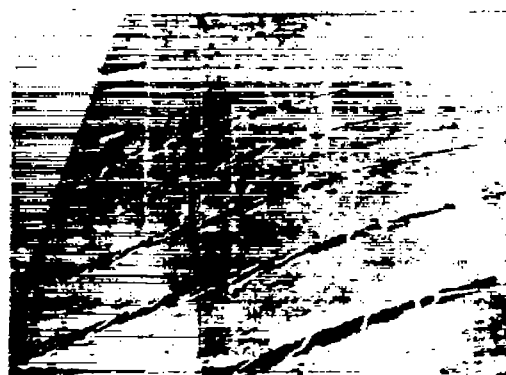
Unsteady Flow
 $C_L = 0.1$



Unsteady Flow
 $C_L = 0.2$



Unsteady Flow
 $C_L = 0.3$

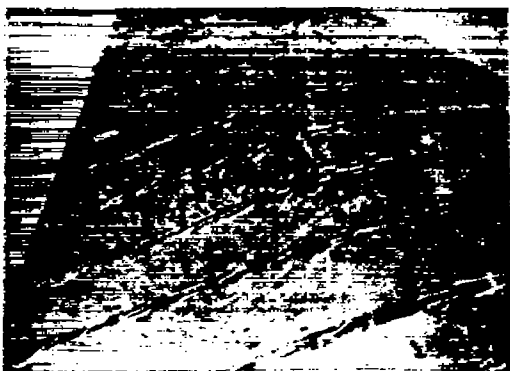


Unsteady Flow
 $C_L = 0.4$

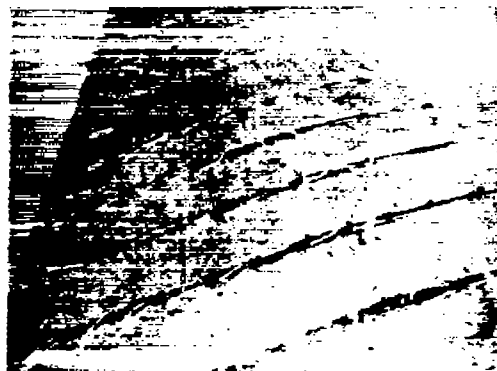
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(d) $M = 0.73$

Figure 3.- Continued.



Unsteady Flow
 $C_L = 0.1$



Unsteady Flow
 $C_L = 0.2$



Breakaway Flow
 $C_L = 0.3$



Breakaway Flow
 $C_L = 0.4$

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(e) $M = 0.75$

Figure 3.- Continued.



Breakaway Flow
 $C_L = 0.1$



Breakaway Flow
 $C_L = 0.2$

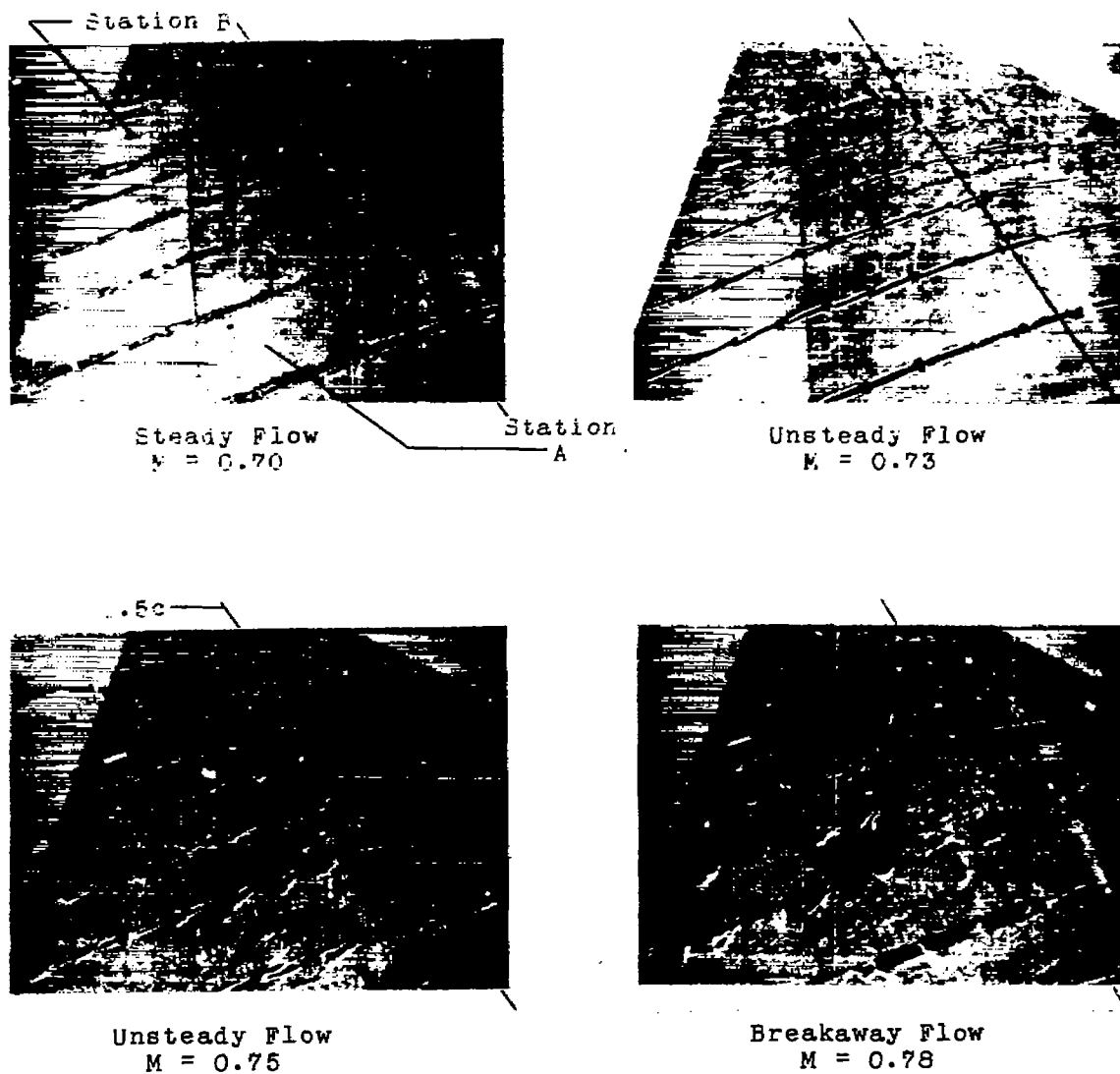


Breakaway Flow
 $C_L = 0.3$

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(f) $M = 0.78$

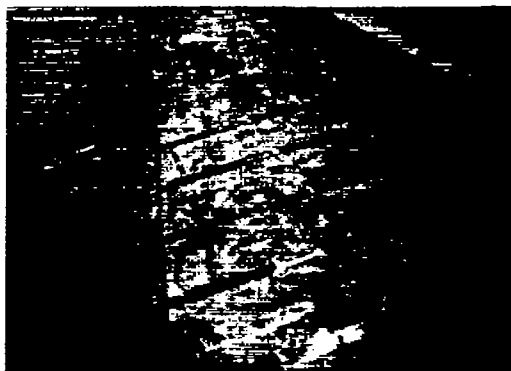
Figure 3.- Concluded.



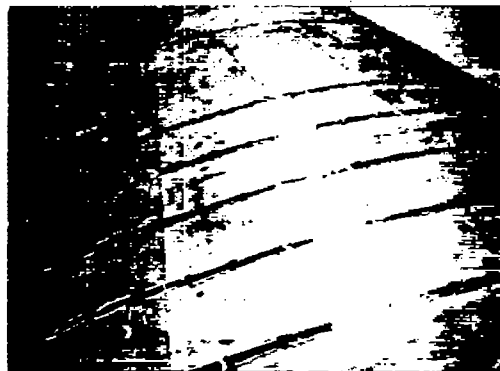
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(a) $C_L = 0.1$

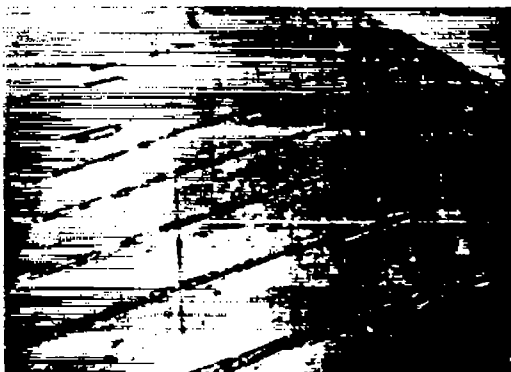
Figure 4.- Photographs of tuft behavior on the upper surface of the XP-51 wing at various Mach numbers.



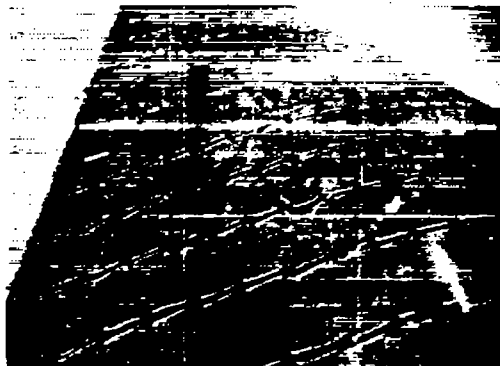
Steady Flow
M = 0.55



Steady Flow
M = 0.65



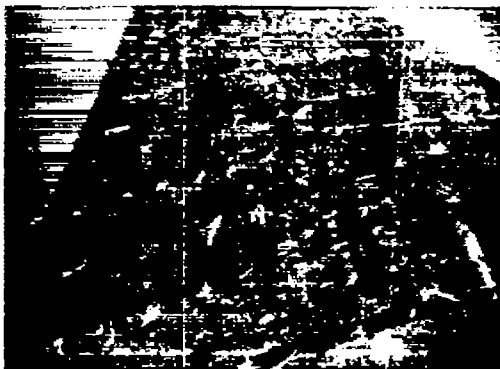
Steady Flow
M = 0.70



Unsteady Flow
M = 0.73



Unsteady Flow
M = 0.75

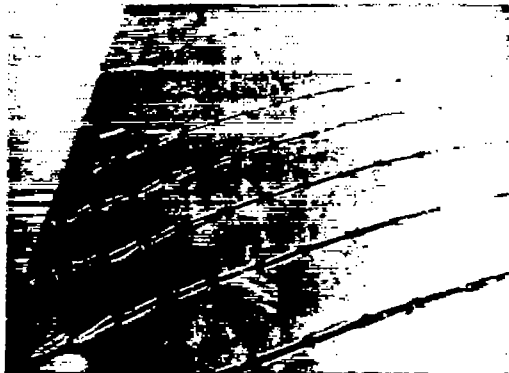


Breakaway Flow
M = 0.78

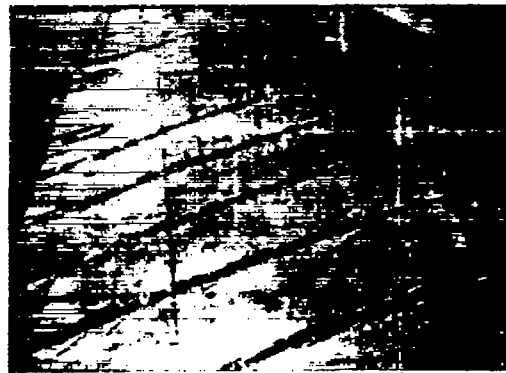
(b) $C_L = 0.2$

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Figure 4.- Continued.



Steady Flow
 $M = 0.65$



Steady Flow
 $M = 0.70$



Unsteady Flow
 $M = 0.73$



Breakaway Flow
 $M = 0.75$



Breakaway Flow
 $M = 0.78$

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(c) $C_L = 0.3$

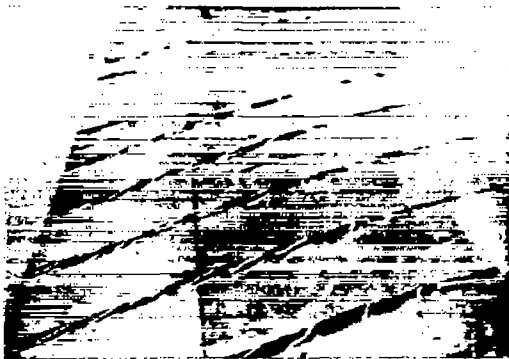
Figure. 4.- Continued.



Steady Flow
M = 0.65



Unsteady Flow
M = 0.70



Unsteady Flow
M = 0.73



Breakaway Flow
M = 0.75

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(d) $C_L = 0.4$

Figure 4.- Concluded.

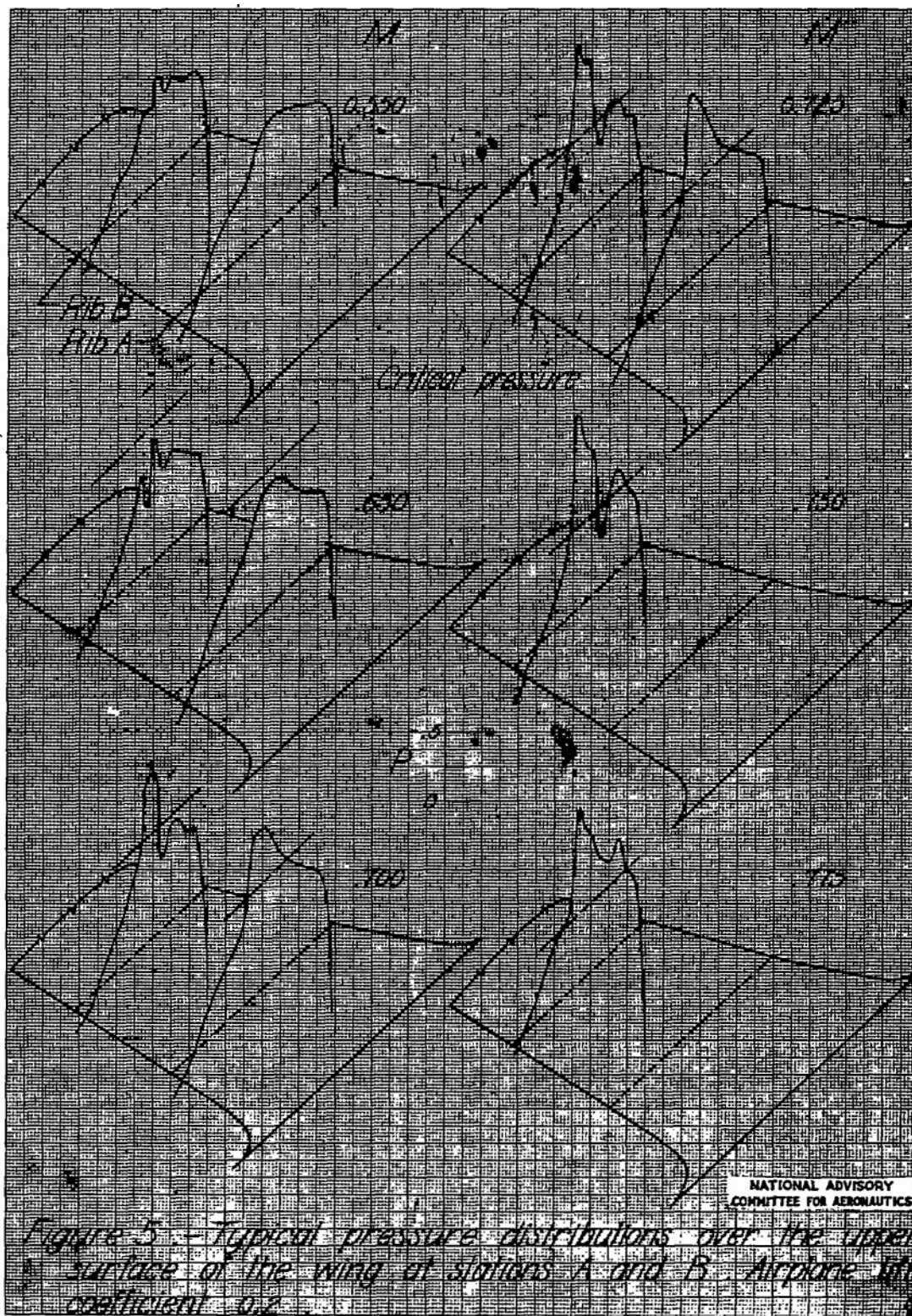
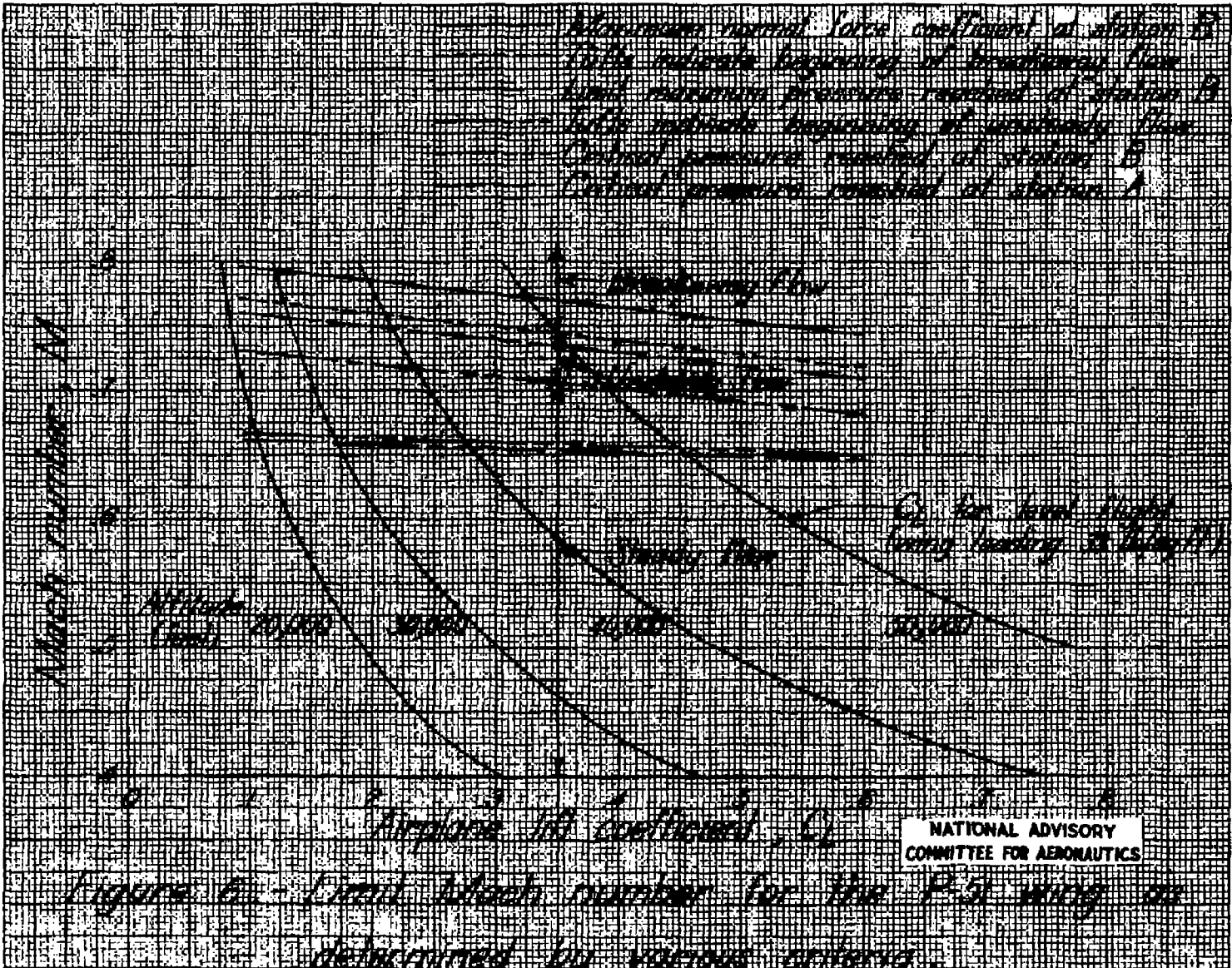
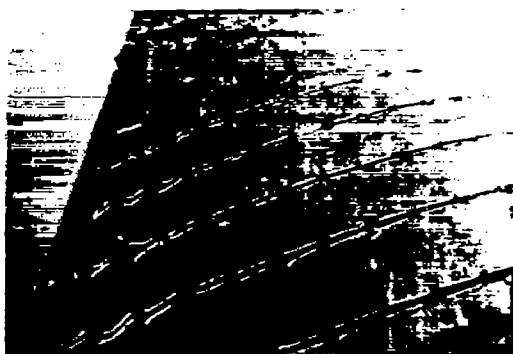


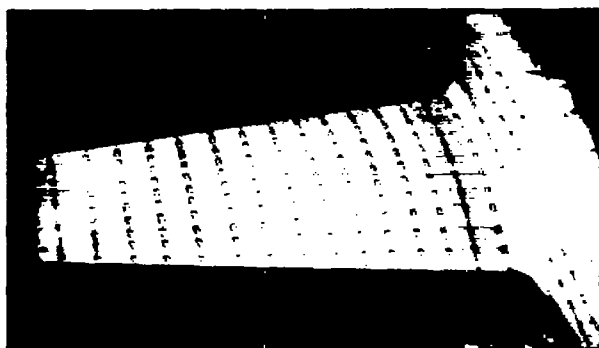
Figure 5 - Typical pressure distributions over the upper surface of the wing at stations A and B. Airplane lift coefficient 0.2





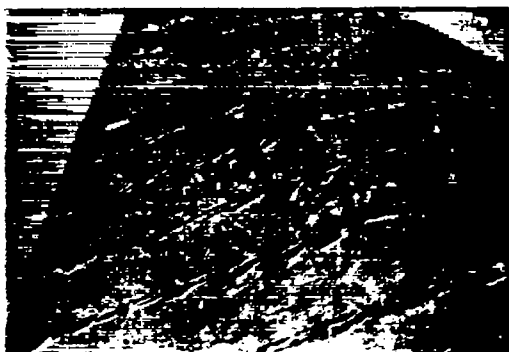
$C_L = 0.60$

$M = 0.65$



$C_L = 0.60$

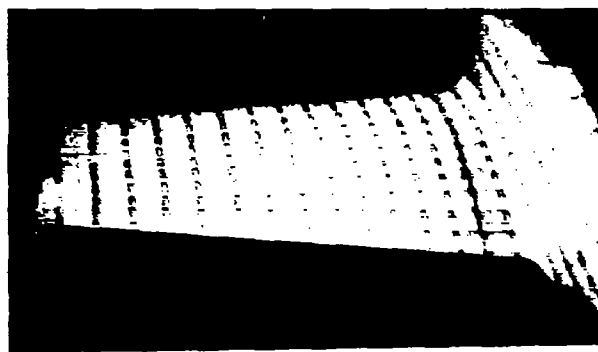
$M = 0.65$



$C_L = 0.10$

$M = 0.75$

Flight



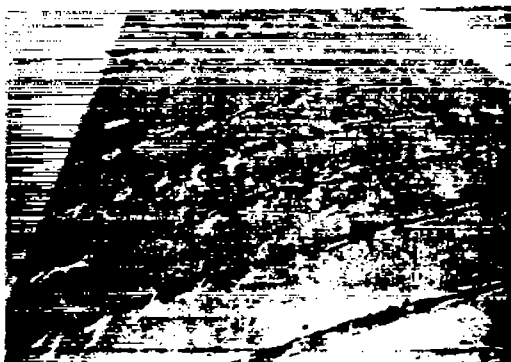
$C_L = 0.04$

$M = 0.75$

Wind Tunnel

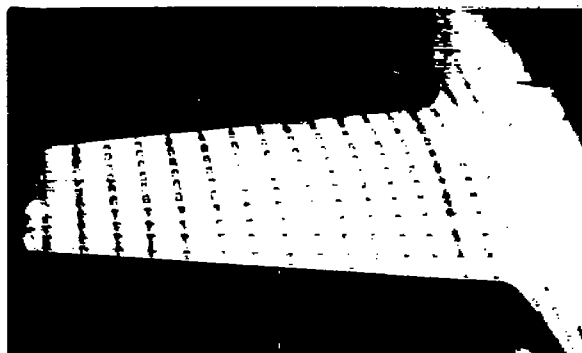
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Figure 7.- Comparison of flight and wind tunnel
tuft surveys.



$C_L = 0.30$

$M = 0.75$



$C_L = 0.30$

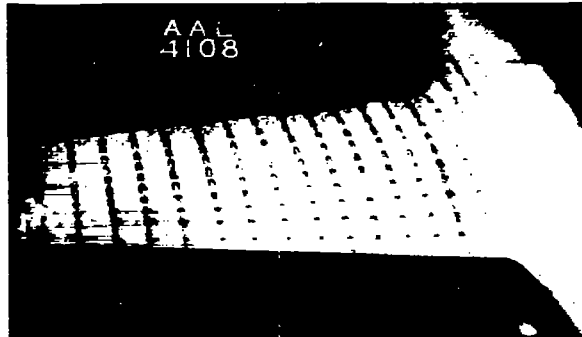
$M = 0.75$



$C_L = 0.10$

$M = 0.78$

Flight



$C_L = 0.04$

$M = 0.79$

Wind Tunnel

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Figure 7.- Concluded.

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ABSTRACT

Wing surface tuft photographs and chordwise pressure distribution measurements made in flight are studied and compared with those obtained from wind-tunnel tests. Comparisons show similar tuft behavior for Mach test range of from 0.55 to 0.78 and lift coefficient test range of 0.10 to 0.90. Steady flow over wing was obtained until critical speed was exceeded by about 0.05 in Mach. Above this, flow over rear 50° of chord became rough at maximum pressure coefficient.

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