FLIGHT RESEARCH

FLOW VISUALIZATION

George Cooper, George Rathert, or Harvey Brown

When we flight test an airplane or place a model in a wind tunnel, our experimental investigation of the aerodynamic forces acting on the model is usually limited to two questions; How large the total forces are, and how they are distributed on the surface of the model. Quite often, however, the total forces and the surface pressure distributions show abrupt changes or other unusual characteristics which cannot be understood or explained without also knowing something about the pressure or velocity field in the airstream some distance away from the surface of the model.

It is necessary, therefore, to supplement our conventional force and surface pressure-distribution measurements with some sort of survey of the variation of pressure and velocity in this external flow field. Two general methods are now in use; direct measurement accomplished by inserting probes or survey rakes, and visualization of the flow, either by tufts and smoke trails, or by various optical means. The optical methods of flow visualization are undergoing intensive development and have become exceedingly important tools in experimental investigations of the aerodynamics of high-speed flows.

We are going to review for you the three principle experimental flow visualization techniques. Because of the limited time it is impossible to deal with the theoretical background adequately; therefore, the object of the discussion will be limited simply to giving you an opportunity to associate the name of each instrument with its degree of mechanical complexity, the amount and type of information about the flow field which it yields, and a sample of the type of records which it is used to produce.

The simplest technique is known as the shadowgraph. A typical set-up for use in a wind tunnel is shown on this slide (fig.7(b)) in which the wing panel being tested can be seen mounted against the far tunnel wall. The only equipment required is an intense point or line light source placed directly opposite the wing pannel, a viewing screen, in this case the tunnel wall, and a camera for making permanent records. The rays of light passing through the flow field are refracted or bent different amounts in the regions of varying density or pressure. A front or region of rapid pressure change will bend enough light to cause a shadow or outline image to form on the screen. In this simple form the shadowgraph method is used chiefly to determine the position and motion of very strong pressure discontinuities such as shock waves. With this method, we can tell where the pressure changes but it is not sufficiently sensitive to tell us how much it changes.

The shadowgraph technique will be illustrated by a test sequence in which the set-up shown in the slide was used to investigate the cause of aileron flutter at transonic flight speeds. The image of the shock wave on this wing panel is projected on the tunnel wall and you can see quite clearly the relationship between the aileron flutter and a fore and aft oscillation of the wing shock wave.

The first step up in complexity and sensitivity is the well-known schlieren apparatus, the basic elements of which are shown schematically on this slide (fig. 7(c)). The equipment consists of a line light source, a condensing lens to provide a uniform "stream" of parallel light which is passed through the flow field, a focussing lens, a knife edge, and a viewing screen or recording camera. Light rays bent or refracted while passing through the flow field will not pass exactly through this focal point. When the knife edge is placed at the focus in such a manner that it intercepts most of this refracted light, the intensity of the light at any point on the screen is reduced an amount proportional to the change in density or pressure along the path through the flow field. With the knife edge properly located the schlieren method provides a very sensitive qualitative indication of the distribution of the pressure changes throughout the flow field.

This sample of schlieren photography shows the model test station of the Ames 8- by 8-inch supersonic wind tunnel during the process of bringing the tunnel up to speed. You are observing the shock wave moving down from the tunnel throat, past the model, and the establishment of the regular supersonic flow pattern about the model at the test Mach number 1.2.

The most complex and most sensitive method of flow visualization is the interferometer, shown very schematically in this slide (fig. 7(d)). The light from the source, condensed to a parallel beam, is split up into two separate beams by a semi-transparent mirror. One beam is passed through the flow field, and the other is transmitted along a path through air which remains at rest throughout the tests. The two separated beams are then recombined in such a manner that the light waves interfere with each other and set up a pattern of interference fringes on the viewing screen. When the tunnel air is at rest a set of parallel lines is formed, and with the tunnel in operation the variations in pressure in the flow field cause the fringes to be distorted or shifted an amount which can be measured and used to compute the point-to-point pressure distribution, starting from some one point at which the pressure is known. An interferometer is quite difficult to adjust and maintain but once placed in proper operation it will give sensitive and complete quantitative pressure-distribution measurements throughout a two-dimensional flow field.

Samples of the interferometer work are presented in the form of a slide showing both the horizontal pattern with the tunnel air at rest (fig. 7(e)) and the condition with the tunnel in operation (fig. 7(f)) showing the shifted displacement of the fringes corresponding to the pressure distribution. You can see the shifted fringes forming the outline of the bow wave about the sphere used as the model.

The value of the preceding technique in interpreting and understanding high-speed flow phenomena in wind-tunnel and ballistics research has been well established for quite some time. However, the question always remains as to how the same flow fields look in free flight at full-scale Reynolds numbers. The Flight Research Section at Ames has been investigating the possibilities of applying two of these techniques to full-scale flight tests. Shadowgraph pictures have been made using the sun as a light source and following the piloting technique shown on this slide (fig.7(g)) where the shock wave formed on a cockpit bubble canopy is used as an example. The airplane is placed in a dive and alined with respect to the sun so that the shadow of the canopy is thrown on the opposite wing, which serves as a viewing screen in the same manner that the wind-tunnel wall was used previously.

In this movie sequence you see the canopy shadow in place on the wing and as the airplane picks up speed, you see the formation of a strong normal shock wave directly over the thickest portion of the canopy. These pictures were taken during a dive to 0.74 Mach number. The camera is mounted directly behind the pilot in the canopy.

The second flow visualization method tested in flight is the schileren apparatus. A complete schlieren set-up with a built-in light source and recording camera has been installed in the P-51H airplane just outside the door (fig. 7(h)). The optical equipment is submerged in the left wing and arranged so that it will photograph a cross section of the flow over the wing between two lenses contained in fairings projecting above the wing skin.

In these pictures you see the intersection of the base of the main wing shock wave and the top of the boundary layer at the test station. The top of the wing skin is here and the flow is moving back from the right-hand side of the picture. The camera speed is 48 frames per second and the full size diameter of the area. These are the first pictures of their type obtained and we have not done much interpretation as yet. The oscillation of the main wing shock wave which is shown here has also been observed by the flight shadowgraph method and the oscillation is even more severe at higher Mach numbers. These pictures were taken at an airplane Mach number of 0.70.

Both the flight shadowgraph and the schlieren methods are still under development; however, we hope to use these techniques to study the correlation between airplane buffeting and the oscillation of the wing shock wave, and to investigate the interaction between the wing shock wave and the boundary layer.

LOW-SPEED CHARACTERISTICS OF HIGH-SPEED AIRPLANES

Howard Matthews, Charles Liddell, or Seth Anderson

The use of highly swept-back and triangular wings for the purpose of delaying and minimizing compressibility effects introduced new stability and control problems at low speeds. It became necessary, therefore, to investigate the extent to which these characteristics could be comprised in order to retain the high-speed advantages offered by such plan forms. I shall describe briefly only a few of the more interesting points uncovered during two typical investigations included in the over-all program.

In order to investigate the effect of sweepback on low-speed flying qualities the Navy in 1946 authorized modification of a Bell P-63 airplane to incorporate swept-back wings. This modification, designated the L-39, is shown on this photograph (fig. 7(i)). The sweepback was accomplished essentially by rotating the quarter-chord line of the outer wing panels to 35°. The data for the following charts on the L-39 which I shall show you were obtained from flight measurements made at Langley Field.

Longitudinal stability is evidenced by the variation of increasing up-elevator for equilibrium with decreasing speed. As indicated on this chart (fig. 7(j)), the unslotted configuration was unstable showing a tendency to nose up at the stall, requiring increasing down-elevator for balance. However, as shown by the yellow curve, use of the wing slots improved the longitudinal stability at the stall to give a favorable pitching down tendency of the airplane.

The most pronounced effect of sweepback on the lateral characteristics is the large increase in dihedral effect with lift coefficient. The dihedral effect is measured by the rolling moment produced by sideslip, and is apparent in flight by the amount of aileron deflection required to maintain equilibrium in steady straight sideslips. The variation of dihedral effect with lift coefficient is shown for one configuration on this chart (fig. 7(k)). It is seen that at low lift coefficients or high speeds, a small amount of negative dihedral was observed. As speed decreased and lift coefficient increased the dihedral effect rapidly increased, and near the stall reached a value equivalent to a geometric dihedral of 20° for a straight wing airplane. It had been expected that such a large dihedral effect might lead to dangerous dutch roll tendencies and objectionably large lateral trim changes in landing approaches. The pilots of the L-39, however, objected only mildly to these high dihedral effects at low speeds. A more objectionable characteristic was the slight negative dihedral effect at high speeds, since the rolling velocity due to rudder deflection was now in the wrong direction.

The L-39 has also been flight tested with different vertical tail areas and the results gave a good indication of the amount of directional stability which should be provided on an airplane with swept-back wings. With directional stability comparable to that of conventional airplanes, the behavior of the L-39 was poor at low speeds due to the large yawing and rolling motions which followed any disturbance. However, when the directional stability was doubled the sideslipping motions and the ensuing rolling motions were reduced to satisfactory magnitudes.

Another high-speed configuration which appears to offer usable low-speed stability characteristics is the triangular wing plan form. Recently an investigation of such plan forms was made in the Langley free-flight tunnel, in which dynamically scaled models can be actually flown, free of support, by remotely located pilot. The triangular plan forms investigated had leading-edge sweepback angles of 53° to 83°. The results of this investigation are summarized on this chart (fig. 7(1)). It was found that the wings of least sweepback had the most satisfactory combination of longitudinal and lateral flight characteristics. However, even these models did not make as satisfactory flights as some conventional airplane models. The power-off glide angles, for instance, were very steep at high lift coefficients, a characteristic which leads to undesirable flight attitudes and high sinking speeds in landings.

As seen on the chart, as sweepback was increased, there was a mild deterioration in longitudinal stability at high lift coefficients and a rapid depreciation in lateral characteristics. The models with very high sweep had constant amplitude or unstable rolling motions which are attributed to the very low damping in roll of such plan forms.

Motion pictures of these two models in the free-flight tunnel will now be shown.

This is the power cable for the control-surface actuators. - - These models were flown exclusively by use of the elevator and aileron control, the trailing-edge surfaces being deflected together for elevator control and differentially for aileron control. - - - It is seen that relatively steady flight could be accomplished without excessive use of the controls. - - - The angular motions that you see here correspond to those of a similar full-scale airplane. - - The next movie sequence is very short due to difficulty in controling the model.

In conclusion I wish to emphasize that we have given you a brief glimpse of the results of only two investigations of the NACA's extensive research program on low-speed stability and control of high-speed configurations. Much more work needs to be done to provide suitable design criteria for a good combination of high- and low-speed characteristics.

The next speaker will be Mr.______ whose subject will be Pilot escape from High-Speed Aircraft.

PILOT ESCAPE

Howard L. Turner or Norman McFadden

The provision for the safe escape of a pilot in an emergency during any condition of flight has become a serious problem because of the high speeds now possible with current aircraft. The problem can be resolved into two parts; first, the safe removal of the pilot from the stricken aircraft, and second, the deceleration of the pilot to a safe landing speed without exceeding the physical limitations of the human body.

This chart (fig. 7(m)) shows four of the methods of escape now being used or being considered and the approximate maximum speeds at which they can be used.

The direct parachute escape is practical only at relatively low impact pressures and consequently can be used only at low speeds. At speeds in excess of 350 miles per hour, the impact pressure could inflict severe damage to any unsupported portion of the body and could make it difficult if not impossible for a pilot to climb out of the cockpit and dive clear of the airplane.

The pilot ejection seat is a force propelled seat designed to support the body of the pilot and to literally throw him clear of the airplane. With suitable protection and proper restraint of the head and the limbs, escape by this method may be possible up to about 500 miles per hour. However, care must be exercised in the design of the ejection system to avoid exceeding the physical limitations of the pilot in the attempt to attain the necessary seat velocities to throw the pilot clear of the tail.

The cockpit capsule is similar in principle to the ejection seat except that the pilot's cockpit or cabin is ejected as a unit thereby protecting him from injury by the pressure of the air stream. Although this method is usable at higher speeds than the ejection seat, the problems of spinning and tumbling and of slowing down the capsule become serious at these speeds.

With a jettisonable nose, the entire nose of the airplane is ejected from some station aft of the pilot's compartment. The pilot escapes after the velocity of the nose section has been sufficiently reduced. The more important problems of nose jettisoning are: first, the successful separation of the nose section from the airplane; second, preventing ramming of the nose section by the main body; third, the stabilization of the nose section to prevent spinning and tumbling; and fourth, the subsequent slowing down of the nose section to a safe speed for the pilot to execute a direct parachute escape.

Results of both static and dynamic tests indicate that some type of hydraulic, pneumatic, or explosive device will be required to insure successful and continued separation of the nose, especially at supersonic speeds. Investigations of several properly ballasted nose sections have indicated an inherent end-over-end tumbling motion which, at very high speeds, may result in tumbling accelerations of the order of 20 g's - - well beyond the tolerable limits of the pilot. In general, it has been indicated that both a forward center-of-gravity position and stabilizing fins are essential for stable descent.

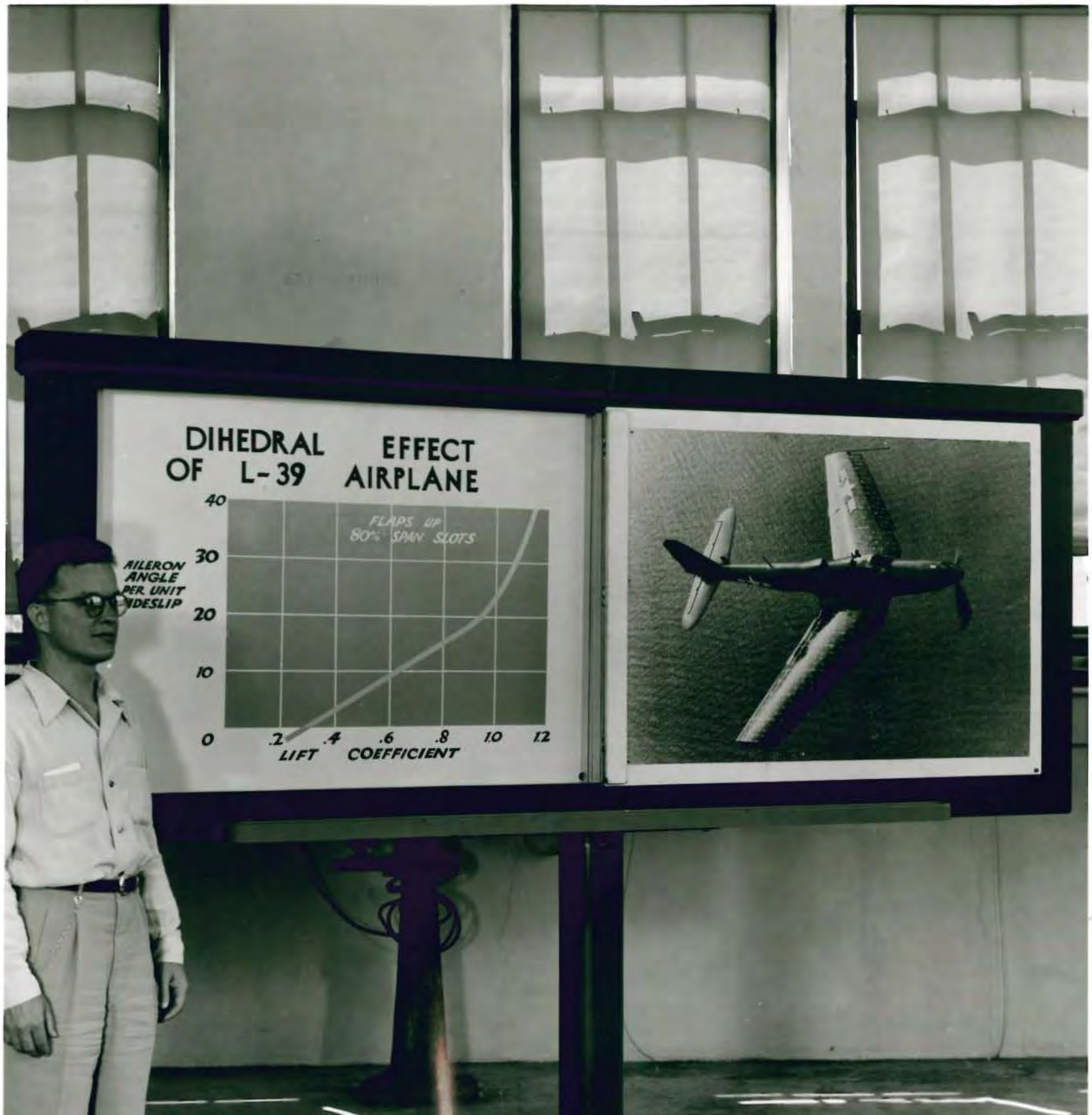
Parachutes and trailing sleeves have been suggested both to stabilize and to slow down the nose section, but it has been found that these devices are not effective means of attaining stability and offer the additional hazard of becoming entangled with the main body. To slow the nose section down to a safe bail-out speed it appears that some form of drag break is necessary.

The following movie illustrates some of the nose jettison work that has been done at low speeds in the Langley free-flight and free-spinning tunnels.

Start movie....

End movie......

Pending actual flight tests, the fully stabilized jettisonable nose, with some provision to prevent ramming by the main body, is being viewed with considerable favor as a solution to the pilot escape problem, especially at transonic and supersonic speeds.



(a) General view.

Figure 7.- Flight-research exhibit.

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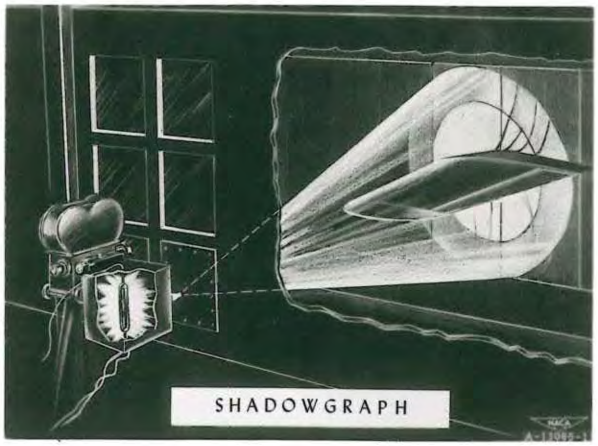
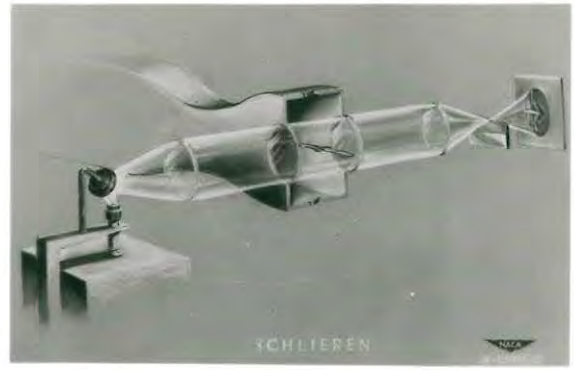
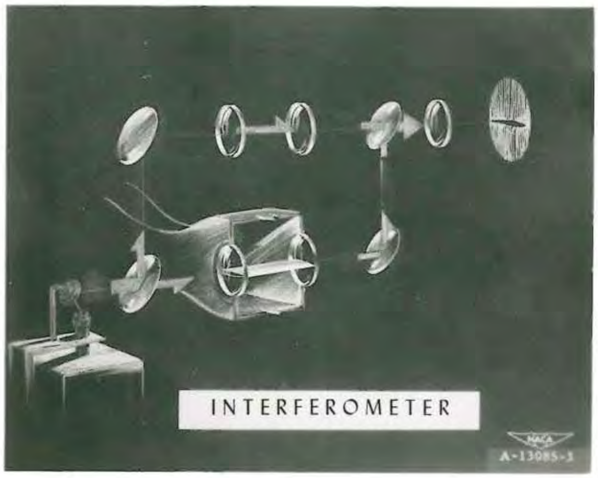


(b) First slide.



(c) Second slide.



(d) Third slide.

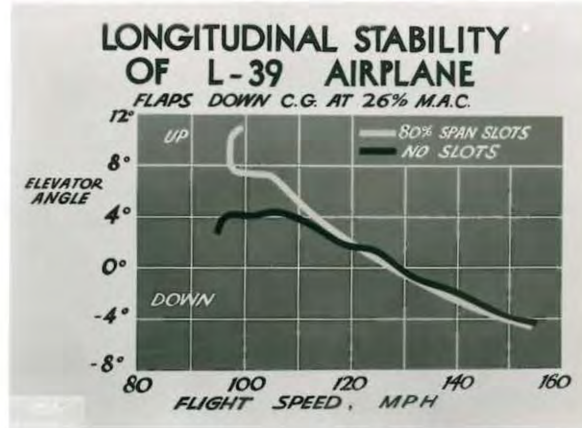
(e) Fourth slide. (f) Fifth slide.

(g) Sixth slide.

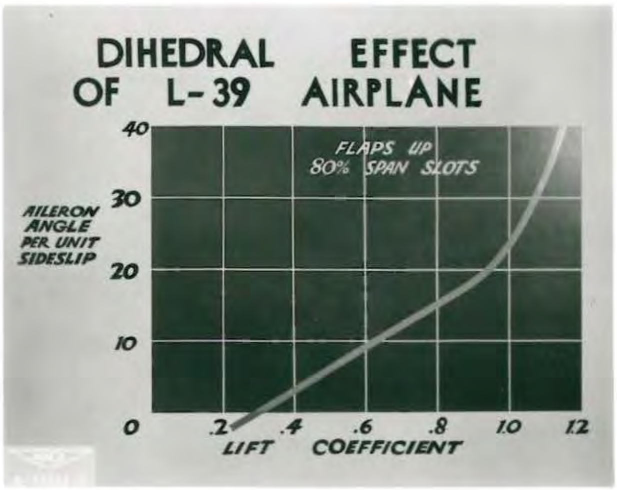
(h) Wing schlieren installation.

Figure 7.— Continued

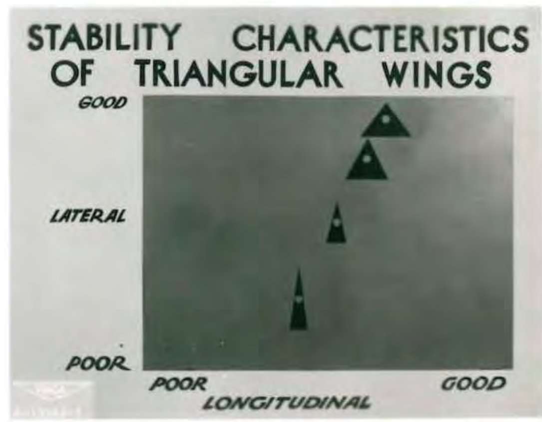
(i) First chart.



(j) Second chart.



(k) Third chart.



(l) Fourth chart.

(m) Fifth chart.

Figure 7.– Concluded.

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