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FOR OPERATION UNDER ICING CONDITIONS

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FLIGHT INVESTIGATION OF A STALL-WARNING INDICATOR
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SUMMARY

A preliminary investigation was made to determine whether some characteristic of the boundary layer could be used to provide satisfactory warning of the increase in the stalling speed of a wing caused by ice formations on the leading edge. The tests were conducted with a Lockheed 12A low-wing, twin-engine, all-metal transport airplane. Wooden strips were used to simulate the ice formations and total-pressure surveys were taken near the trailing edge behind the wooden strips as the airplane was stalled. Most of the stalls were made in level flight in the following conditions: (1) cruising, 80-percent rated power; (2) glide, power off, flaps retracted, landing gear up; and (3) approach, power off, flaps fully deflected, landing gear down. These flights were supplemented by a few stalls, in only the cruising condition, in which the airplane was banked to produce normal accelerations ranging from 1.2g to 1.6g.

The most promising characteristic of the flow near the trailing edge that might be used as a warning of impending stall was the decrease in total pressure at a given level above the wing surface to a value slightly above free-stream static pressure as the airplane speed was reduced.

INTRODUCTION

The development of stall-warning indicators has long been considered desirable because of the dangers associated with the unexpected stalling of an airplane and because inherent warnings (such as tail buffeting) frequently are not satisfactory. The requirements for an entirely satisfactory stall-warning indicator are very severe. Adequate and consistent warning should be provided with the airplane
in any condition of power or flap deflection, with the wing loading changed because of variations in gross weight or because of maneuvers, and with the local stalling speed of any portion of the wing increased by ice formations on the leading edge. Previous investigations by the NACA (reference 1) have produced a stall-warning device meeting all of the listed requirements with the exception of providing warning of increased local stalling speeds caused by ice formations. The provision of warning for a wing on which ice has formed presents a double problem because the stalling speed of the wing as a unit is increased an unknown amount and also because the sequence of stalling of adjacent sections may be altered.

The present test program for developing an indicator to satisfy the foregoing requirements consists of two parts. The first part is the determination of a basis for stall warning at one section of the wing when that section is made to stall prematurely by placing simulated ice formations on the leading edge. Surveys were made on the upper surface near the trailing edge to determine the effect of the formations on the air flow over the wing section as the airplane was stalled. The second part of the test program consists of the extension of the surveys to the rest of the wing in order that a series of indicators located spanwise can be used to show the sequence of section stalling. Preliminary tests covering the first part of this program have been conducted by the NACA at the Langley Memorial Aeronautical Laboratory and the results are reported herein.

APPARATUS

The airplane used for the investigation is a Lockheed 12A, twin-engine, low-wing monoplane shown in figure 1. The wing details are shown in figure 2. The wing has a span of 49.5 feet, split flaps lowering to a fully deflected position of 45°, and ailerons that droop 9.5° when the flaps are fully extended.

Ice accretion on the wing was simulated by fastening wooden strips with masking tape to the de-icer attachment strip on the upper surface at about 50 percent semispan from the plane of symmetry. (See fig. 2.) Two strips were used—one of which was semicircular in cross section, 3 feet long, and 1/4 inch high and the other was triangular
in cross section, 2 feet long, and 1/2 inch high.

The rake used in making the pressure surveys at the trailing edge (see fig. 2) consisted of six tubes: one static-pressure tube and five total-pressure tubes. The total-pressure tubes were spaced 1/2 inch, and the lowest tube was 1/2 inch above the wing surface. The rake was located 12 inches forward of the trailing edge and behind the center of the wooden strip on the leading edge.

The static and total pressures measured with the rake were referred, respectively, to the free-stream static and total pressure measured with an airspeed head mounted about one chord length ahead of the wing tip. (See fig. 1.) A swiveling type of airspeed head that aligns itself with the local flow was used to keep to a minimum the variation with speed of the static pressure measured by the airspeed head. The static-pressure orifices of the swiveling head were calibrated by means of a suspended trailing airspeed head. (See fig. 3.)

Several tufts were distributed over the wing to allow the observer to correlate the progress of stall with the measurement of pressures at the rake.

All pressures were recorded by an NACA recording manometer and correlated by means of an NACA timer. For a few of the tests, the normal acceleration at the center of gravity of the airplane was recorded by an NACA recording accelerometer.

PROCEDURE

Pressure records were taken as the airplane was gradually stalled in the following conditions: (1) cruising, 80-percent rated power; (2) glide, power off, flaps retracted, landing gear up; and (3) approach, power off, flaps fully deflected, landing gear down. The action of the tufts was continuously observed, and the approximate time at which more than one-half the tufts behind the wooden strip reversed their normal direction and then fluctuated forward and rearward was taken as the section stall. At that time, the switch controlling the manometer and timer was momentarily opened to identify the section stall condition on the pressure records.

Information concerning the effect of wing loading on
the pressures recorded at the rake was obtained during several stalls made in a cruising condition as the airplane was banked to increase the normal acceleration.

RESULTS AND DISCUSSION

The data obtained in these preliminary stall tests have been analyzed by referring total pressures at the rake to (1) free-stream total pressure, (2) static pressure at rake, (3) free-stream static pressure, and (4) static pressure from wing-tip swiveling head.

Total pressures at rake referred to free-stream total pressure.- With no simulated ice on the leading edge, the differences between the total pressures given by the three lowest rake tubes and the free-stream total pressure did not change sufficiently, as the airplane was stalled to serve as a warning. The rest of the rake total-pressure tubes, however, indicated an appreciable loss in total pressure as the section stalling speed was approached.

With the triangular strip mounted on the leading edge to simulate ice, however, the disturbance was so great that a loss in total pressure equivalent to free-stream dynamic pressure $q$ at an airplane speed of 90 miles per hour, and equivalent to one-third free-stream dynamic pressure at an airplane speed of 160 miles per hour, was registered by a rake total-pressure tube 2.5 inches above the wing surface. Because of this large loss in total pressure, the use of the difference between rake total pressure and free-stream total pressure as a basis for stall warning was not considered feasible.

Total pressures at rake referred to static pressure at rake.- The local indicated velocities as determined from the difference between the rake total pressures and the rake static pressure were plotted against the difference between the indicated airplane speed and the speed corresponding to test-section stall. Figure 4 is representative of these plots and shows the indicated velocity at the rake total tube 1 inch above the wing surface for the condition with the half-round strip on the leading edge. The curves of this figure indicate a decrease in the local velocity at a rate that would provide a good basis for a stall-warning indicator but possess an undesirable feature in the high velocities attained in the ap-
proach condition. These high velocities were produced by lowering the flaps, and their presence would require the indicator setting to be a function of flap position. For example, if the stall-warning device were set to operate at a pressure corresponding to a local velocity of 45 miles per hour, reasonable warnings of 9.5 and 14 miles per hour would be obtained for the glide and cruising conditions, respectively, but practically no warning would be provided for the approach condition. The indicator would have to operate at a local velocity of about 67 miles per hour to provide a satisfactory warning for the flap-deflected condition. This undesirable feature of changes in the indicator setting should be avoided, if possible, although a mechanical connection between the flap and the warning device to change the pressure at which the warning device would operate is conceivable.

Total pressures at rake referred to free-stream static pressure.—The possibility of including the flap-deflected condition in a single indicator setting was presented when the rake total pressures were referred to free-stream static pressure and were plotted against the difference between the airplane speed and the speed for test-section stall. Figure 5 shows this plot for the rake total-pressure tube 1 inch above the wing surface for the two types of strip used to simulate ice. This figure shows that, by setting an indicator to operate when the difference between the total pressure 1 inch above the wing surface and the free-stream static pressure drops to a value of 0.3 inch of water, warning (ranging from 7 to 14.5 mph) would be provided for all the test conditions. The indicated airplane speeds for section stall in the cruising, glide, and approach conditions were 86.5, 91.5, and 73.5 miles per hour, respectively, with the half-round simulated ice strip and 93.5, 107, and 79 miles per hour, respectively, with the triangular strip.

The two curves for each airplane condition in figure 5(b) are the result of fluctuations in the total pressure at the rake. These fluctuations could probably be greatly reduced by introducing damping in the tubes connecting the rake total-pressure tubes to the manometer; the warning points in figure 5(b) have been selected, therefore, as midway between the two curves for each airplane condition.

No curves are presented for the condition of no ice on the wing because the portion of the wing surface shown as the shaded area B in figure 2 always stalled first
with power off and sometimes stalled first with power on. Surveys have not yet been made in area B, but the indicator located in that region would probably be the first to provide warning when no ice was present on the wings.

Figure 5 indicates that the loss in total pressure at the trailing edge of an airfoil referred to free-stream static pressure may serve as a basis for warning of approaching stall. In any practical application, however, the total pressure cannot be referred to free-stream static pressure. Furthermore, the magnitude of the ordinates in figure 5 reveals that variations in the pressure used as the reference source will have considerable effect upon the degree of warning provided. For example, if a warning indicator were set, as shown in figure 5(a), to provide a 10-mile-per-hour warning in the cruising condition, a change in the reference static source equal to 5 percent of the free-stream dynamic pressure at cruising stall would change the amount of warning provided by 2 miles per hour.

Total pressures at rake referred to static pressure from wing-tip swiveling head.—The effect of referring the variation of total pressure at the rake to the static pressure from the wing-tip swiveling head, which is a source similar to that usually available in flight operations, is shown in figure 6. The variations in the static pressure from the swiveling head are shown in figure 3. The effect of these variations on the degree of warning provided can be determined by a direct comparison of figures 5 and 6, inasmuch as the indicator setting has been taken to be the same for all four figures.

Effect of wing loading.—The effect of wing loading on the stall warning provided for the cruising condition, with the half-round wooden strip on the leading edge, is shown in figure 7. The normal acceleration varied by \pm 0.1g for any one stall because of the difficulties experienced in maintaining absolute control of all flight factors. The lower curve indicates the airplane speeds at which stall warning would be given with increasing normal acceleration provided that the warning indicator were set to operate when the difference between the total pressure 1 inch above the wing surface and free-stream static pressure dropped to 0.3 inch of water. The upper curve shows the airplane speeds at which test-section stall was observed for various values of normal acceleration. The degree of warning can be seen to vary from 10 miles per hour with normal wing loading to 16 miles per hour with the wing loading corresponding to a normal acceleration of 1.5g.
Additional surveys.—Further investigations with the indicator located farther outboard than in the previous survey have confirmed the conclusion that, at points where flow conditions are essentially the same as those at the test section previously discussed, the loss in total pressure may serve as a basis for stall warning. Surveys at the trailing edge in the slipstream, however, indicate that the total pressure in the boundary layer is affected by power to such an extent that the variation of loss in total pressure cannot be used as a basis for stall warning in that region.

Limitations of total-pressure-loss type of indicator.—Some uncertainty may exist in a practical application using the variation in total pressure at the trailing edge of the wing referred to some source of constant pressure as a criterion for stall warning, inasmuch as the magnitude of this pressure variation may be so slight as to be influenced by a number of factors affecting the measurement of the reference pressure. One such factor is the location of the source of the reference pressure and another is the change in the physical characteristics of the instrument measuring the reference pressure. An extremely desirable feature of the stall-warning indicator of reference 1 is its ability to produce a pressure variation of large magnitude and, if this characteristic could, by further development, be incorporated in the total-pressure-loss type of indicator, the device would be more practicable to use than it is at the present time.

CONCLUSIONS

A preliminary flight investigation of the flow characteristics near the trailing edge of a wing, as the airplane was stalled with simulated ice on the leading edge, indicated the following conclusions:

1. The loss in total pressure at the trailing-edge rake, when referred to free-stream total pressure, was too greatly influenced by the ice formations to serve as a basis for a warning of the approach of the stall.

2. The change in local velocity at the trailing edge was sufficient and consistent enough to serve as stall warning, but the effect of the deflected flaps on the local velocity would require the indicator setting to be a function of flap position.
3. The difference between the total pressure at the trailing edge and either the free-stream static pressure or the static pressure of the swiveling airspeed head changed sufficiently to serve as a basis for stall warning in all the conditions tested. The variation of total-pressure loss, however, was too small to justify the practical application of this loss as a basis for stall-warning indication; further development would be desirable to produce a large pressure change at the warning device when the total pressure in the boundary layer reached the critical value.

4. For the cruising condition, the degree of section stall warning varied with increasing wing loading from 10 miles per hour with normal wing loading to 16 miles per hour with the wing loading corresponding to a normal acceleration of 1.5g produced by banking the airplane.

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REFERENCE

   T. N. No. 670, NACA, 1938.
Figure 1.- Lockheed 12A airplane used for stall-warning investigation. Swiveling air-speed head installed one chord length ahead of leading edge at right wing tip.
Figure 2.- Location of survey rake and wooden simulated ice strips during stall tests.

Figure 3.- Calibration of the swiveling head mounted at the Lockheed 12A wing tip. $V_1 = \frac{45}{q}$. 

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NACA 23016 airfoil section

De-icer attachment strip, approximately 0.07c from L.E.

$c = 7.12$ NACA 23008 airfoil section

Free-stream static pressure minus swiveling-head static pressure

Indicated airspeed, $V_1$, mph

Free-stream dynamic pressure, $q$, in. of water
Trailing-edge total pressure minus free-stream static pressure, in. of water

Warning (mph)
Approach, 14.5
Cruising, 14.0
Glide, 8.0

Warning indicator set at 0.3 in. of water

Indicated airplane speed above section stall, mph
(a) Half-round wooden strip.
(b) Triangular wooden strip.

Figure 5.— Variation in total pressure 1 inch above wing surface and 12 inches from trailing edge.
Figure 6.- Variation in total pressure 1 inch above wing surface and 12 inches from trailing edge.

(a) Half-round wooden strip.
(b) Triangular wooden strip.