a vortex system consisting of leading edge, tip, and snag vortices causing abrupt changes in flow direction over the surface. The regions of high fluctuating pressures seem to be associated with these vortices, particularly the snag and tip vortices.

No discernible single "convection" mechanism for the transport of the fluctuating pressures was evident such as the downstream convection reported in studies of slender spacecraft launch vehicles. Disturbances seemed to emanate from multiple sources simultaneously and propagated in a complex manner.

Correlation is small between points on the wing that are separated by more than about ¼ of the mean aerodynamic chord.

The fluctuating pressure spectra frequently exhibited peaks at frequencies believed to be associated with vortices. The frequency associated with the snag vortex was generally about half that of the leading edge and tip vortices. These frequencies, scaled to the flight vehicle, were at the higher end of the vehicle's primary structural resonances.

Maximum buffet intensities occurred at the high subsonic Mach numbers diminishing abruptly to small values at sonic and supersonic speeds.

Maximum rms wing root bending moments caused by buffet were of the order of 7% of the corresponding steady bending moments.

Maximum fluctuating pressure coefficients were generally of the order of $\Delta C_{p_{rms}} = 0.2$.

The measurements from this model were used to establish a buffet spectral response method for computing wing vibrations; encouraging agreement with flight measurement was obtained.

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Some Aspects of Airfoil Stall in Low-Speed Flow

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In the process of reviewing some existing data on low-speed airfoil stalling, we find that it is possible to correlate the pressure distributions in the long bubbles of thin-airfoil stalling by using the reduced coordinates originally intended for the separation of base flow. The correlation so obtained bears close resemblance to the one for base flow. An existing correlation curve of leading-edge reseparation is used with measurements on a NACA 0010 and a NACA 66_3-018 airfoils to indicate the possibility of predicting the allowable angle of attack for maximum lift of moderately thick airfoils.

I. Introduction

THE stall of an airfoil is a very complex problem in aerodynamics. The mechanism itself is not fully understood and the parameters involved are many. Thus, it has so far defied theoretical treatment. Recourse is, therefore, made to experimental observations and measurements. Although some systematic efforts have been made, from which a few correlation curves resulted among other things, a large portion of the experimental results can only be found in the form of raw data. In view of this shortcoming, some existing data were re-examined from which we were able, a) to reduce the pressure distributions in the long bubble (thin-airfoil separation) to an almost single correlation curve, and b) to discover a possible utility of one existing correlation representation for predicting the maximum lift and occurrence of stall of a moderately thick airfoil.

Prior to any further discussion, it is worth stating the types of airfoil stall, since its demarcation is by no means unique. The common practice is to classify it into three major categories in low subsonic speed: a) the thin-airfoil stall, b) the leading-edge stall, and c) the trailing-edge stall.[1] The last type occurs generally on thick airfoils and it will not be considered here.

The thin-airfoil separation is usually observed on thin airfoils or on sharp leading-edge airfoils. The flow sepa-

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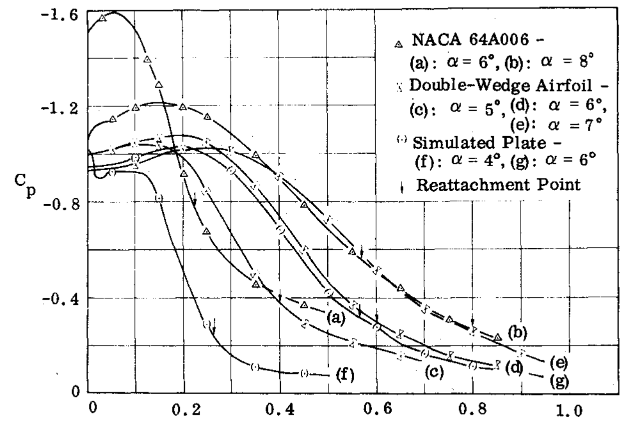

Fig. 1 Pressure-coefficient distributions in the long bubbles of thin airfoils (data from Refs. 1 and 7).

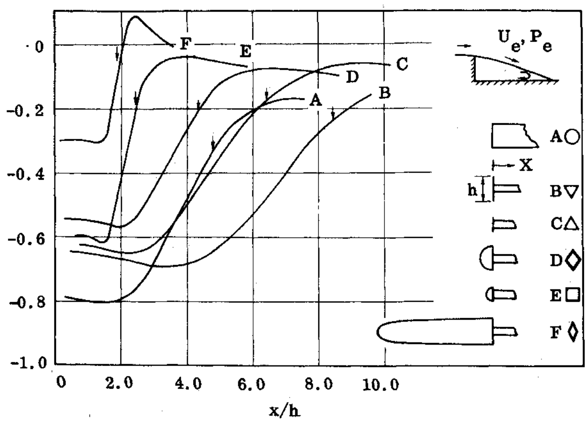

Fig. 3 Pressure distributions of base separation (arrows indicate reattachment points).

rates at the leading-edge but reattaches downstream, thus forming a so-called long bubble. The point of reattachment moves progressively rearward as the angle of attack increases. The airfoil does not in general experience stalling until the reattachment point reaches the trailing edge, and the lift continues to increase with incidence. It is shown here that the pressure distributions in the long bubble of different airfoils can be reduced to a single curve. This constitutes the first-part of our finding.

In the age of ever increasing speed of an aircraft, moderately thick airfoils were deemed to be antiquated. However, since the device of supercritical wings, there has been a renewed interest in this class of airfoils. Consequently, a brief review was made of the leading-edge stall, which is usually the characteristic of a moderately thick airfoil at relatively high angles of attack.

Leading-edge stall usually begins with a laminar-separation bubble (or a short bubble) downstream of the suction peak. Its existence is, however, of little importance, because the extent is short and the effect on the pressure distribution is small. As the angle of attack further increases, a different kind of separation will have to take place to negotiate the large adverse pressure gradient. This radically alters the flow configuration and results in an abrupt change in lift coefficient. This abrupt change is ordinarily identified as the leading-edge stall. Observations, however, indicate that there may be two sub-sets in this class. One is known as the "bubble bursting" and the other "reseparation."[2] The former is characterized by the sudden break away of the reattachment point of a laminar-separation bubble, whereas the latter is the sudden separation of the boundary layer downstream of such reattachment.

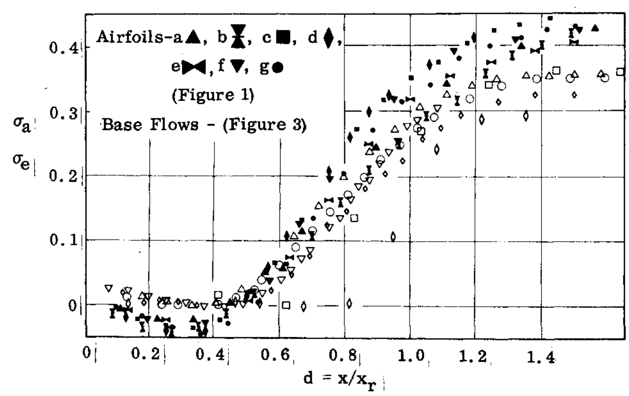

Fig. 2 Pressure distributions in reduced coordinates of base separation and thin-airfoil stall.

In the case of reseparation, a correlation curve was obtained by Evans and Mort,[2] which correlates the suction peak velocity of different airfoils with the distance of adverse pressure gradient. We will show later that a possible use may be made of this curve to aid the prediction of the allowable angle of attack for maximum lift. This constitutes the second part of our finding.

II. Correlation of Pressure Distributions for Thin-Airfoil Separation

Since the airfoil stall and the flow behind a bluff base all belong to the phenomenon of flow separation, it is natural to associate them. However, such association in previous work lacks a clear representation and is not quantitative. In this section a correlation curve for the thin-airfoil separation is presented, in which the pressure distributions on different types of airfoils that appear to be random in the usual pressure coefficient plot (Fig. 1) can be reduced to an almost single curve (Fig. 2) by using nearly the same method as described by Roshko and Lau[3] to correlate base pressure distributions. The marked similarity as is evident in Fig. 2 appears to indicate the state of close association between these two types of separation.

It seems pertinent that a brief review and the possible reasons that suggest similarity are in order before setting down the procedure for reducing the pressure distributions.

Various postulations were made by different investigators to seek a criterion for breakdown of a laminar-separation bubble preceding the stall of an airfoil.[4] In particular, an assumption was put forth by Crabtree[5] that there is a maximum value of the pressure recovery coefficient, σ, above which the breakdown occurs, where σ is defined as $\sigma = (p_r - p_s)/\frac{1}{2}\rho U_s^2$, with p_r and p_s being the pressures at reattachment and separation respectively, and U_s being the velocity outside of the boundary layer at separation. To confirm this assumption, evidence was subsequently provided by both simple theoretical considerations and experimental measurements. The value of σ was found to be approximately equal to 0.36. One set of the measurements made by Moore[6] used a backward facing step to simulate an airfoil separation bubble. The objective was mainly to observe the variation of the pressure recovery coefficient with incidence in the laminar-separation bubble (σ generally increases with incidence) and to verify the existence of its maximum value. Little attention was paid to the pressure distribution in the bubble.

Using a somewhat different pressure recovery coefficient, Roshko and Lau examined a set of pressure measurements in the separated regions of various forebodies with reattachment surfaces (Fig. 3) and they found that all the pressure recovery coefficients were approximately equal. They subsequently introduced reduced coordinates which then correlated the pressure distributions depicted in Fig. 3 to a more or less single curve as illustrated in Fig. 2. These reduced coordinates are defined as follows:

$$\sigma_e = \frac{p - p_e}{1/2\rho U_e^2} = \frac{c_p - c_{pe}}{1 - c_{pe}}, \qquad d = \frac{x}{x_r}$$

where p_e and U_e are the pressure and velocity in the flow approaching separation (see the insert in Fig. 3); x_r is the reattachment distance measured from the shoulder to the reattachment point.

As noted by Roshko and Lau, there seems to be a common feature in all the experiments from which good correlation results. It is characterized by the following conditions: a) the existence of a more or less fixed separation point, b) a thin boundary layer before separation, c) a solid reattachment surface, and d) turbulent reattachment. (Separation from a thick boundary layer such as the case *F* in Fig. 3 exhibits unsatisfactory correlation.) By examination of thin-airfoil separation, we found that it also possesses these properties. For a thin or a sharp-nosed airfoil, separation occurs almost always at the leading edge, thus at a more or less fixed point. Since the stagnation streamline is usually situated near the leading edge for a thin airfoil, the boundary layer at separation is thin. The long bubble reattaches at the airfoil and hence the reattachment is on a solid surface. Finally the reattachment of a long bubble is known to be turbulent, and hence condition *(d)* is satisfied.

To apply the aforementioned reduced coordinates, some modification is needed, for the values of p_e and U_e cannot be easily found. To this end, we define a new set of these coordinates

$$\sigma_a = \frac{p - p_a}{1/2\rho U_a^2} = \frac{c_p - c_{pa}}{1 - c_{pa}}, \qquad d = \frac{x}{x_r}$$

where p_a and U_a are the pressure and velocity at a point chosen arbitrarily to be 5% of x_r from the leading edge, and x_r is the distance between the leading edge and the reattachment point.

Due to the scarcity of measured pressure distributions in the long bubble, only three examples have so far been found.[1,7] They are all plotted in Fig. 1. The point of reattachment on each curve is indicated by an arrow. The pressure distributions were then calculated and replotted according to the reduced coordinates, shown as solid symbols in Fig. 2. As can be seen, they bear close resemblance to those of the base separation. The pressure recovery coefficients for these three examples were found to be around 0.35.

It should be remarked that the points of reattachments for the modified double-wedge airfoil at incidences of 5° and 7° given originally in Reference 1 were not used for the reduced coordinate, since the measurements were considered to be not detailed and refined enough to define these points. Instead, they were taken from the estimated values indicated in Ref. 7 (in particular, extrapolation was employed to determine the location at incidence of 7°). The freestream chord Reynolds numbers of these examples are 4×10^6 for the simulated plate and 5.8×10^6 for the rest. This range of the Reynolds number variation appears to be rather narrow. However, the generally accepted assertion is that the Reynolds number effect on the long bubble is small.

III. Prediction of Angles of Attack for Maximum Lift on a Moderately Thick Airfoil

One of the primary objectives in studying an airfoil is to predict the maximum lift after the geometry is given. Unfortunately this cannot be done analytically in the present state of art; some empiricism must be accepted, short of complete recourse to experiments. Since the question of maximum lift of an airfoil is closely related to the onset of stall, it is natural to go over some empirical relations of stalling to see whether any use can be made of them. One such relation which we came across is the correlation curve of reseparation of the leading-edge stall by Evans and Mort.[2] Inasmuch as the authors did not consider any application, the potential use of this curve is explored in this section. The assumptions and justifications for getting this correlation are, however, not discussed. Reference is made to the original report.

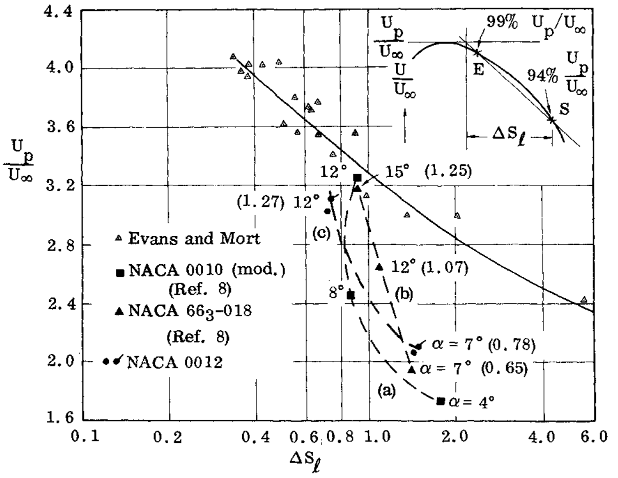

Fig. 4 Prestalling curves and a correlation of stalling peak velocity vs adverse pressure gradient for moderately thick airfoils (numbers in parentheses denote measured lift coefficients).

The open symbols in Fig. 4 which constitute the correlation representation are taken from fifteen different airfoils tested under various conditions. To select these airfoils for the qualification of reseparation of the leading-edge stall, two criteria were invoked. One was that the stall must be abrupt enough so as to insure the leading-edge stalling. For this, the requirement was that the two points of data defining stall should indicate a slope $|\Delta C_l / \Delta\alpha|$ of at least one tenth per degree, with $|\Delta C_l|$ itself being at least one tenth. The symbols ΔC_l and $\Delta\alpha$ are the increments in lift coefficient and angle of attack respectively. The second criterion was to postulate a critical Reynolds number based on the momentum thickness at the laminar separation above which the leading-edge stalls are assumed to occur by reseparation. This critical value was chosen to be 370 in the correlations of Fig. 4.

It was argued in Ref. 2 on a plausible notion that the incipience of reseparation should depend upon the initial thickness of the reattached boundary layer immediately downstream of the laminar separation bubble, which should, in turn, depend upon the steepness of the adverse pressure gradient in the laminar region. Thus, a correlation should exist between the minimum pressure on the airfoil (or the peak velocity U_p) and a length subtended by the initial adverse pressure gradient, when the airfoil is at stall. In order to fix this idea, a representative length was chosen as the percent chord (ΔS_l) between the point of the peak velocity and the point at which the velocity has dropped 6% from the peak value, and subtended by the average slope *ES* between the points of 99% U_p/U_∞ and 94% U_p/U_∞ as indicated in Fig. 4 with U_∞ being the freestream velocity. Each open symbol in this diagram represents the condition at stalling of one airfoil. (One airfoil may sometimes result in two points in Fig. 4 due to both the positive and negative angles of attach, and hence there are nineteen points out of fifteen airfoils.) The correlation is seen to be reasonable.

In so far as this correlation is accepted, a potential use may be made of predicting the allowable angle of attack for the maximum lift on a moderately thick airfoil undergoing leading-edge reseparation. To this end, the following steps are to be taken. We first compute the theoretical velocity distributions on an airfoil at various angles of attack from which the quantities U_p/U_∞ and ΔS_l are determined. (Incidentally, the quantities U_p/U_∞ and ΔS_l used for correlation in Fig. 4 were also theoretical values at an angle of attack immediately prior to stall. For details, see Ref. 2.) We then plot and connect these points shown as (a) or (b) in Fig. 4 to form a curve. Each point corresponds to one value of angle of attack. This pre-stalling curve, since it lies in the lower half of the diagram, will in general intersect the correlation curve, or by extrapolation if necessary. The point of intersection corresponds approximately to the allowable angle of attack before stalling, provided that the aforementioned criteria are satisfied.

To assess the accuracy of this procedure, we found two examples in the literature which are not the ones correlated by Evans and Mort. One is a modified NACA 0010 airfoil and the other a NACA 66_3-018 airfoil. The quantities U_p/U_∞ and ΔS_l in the prestall conditions were obtained from the measured pressure distributions and plotted as curves (a) and (b) in Fig. 4. The upper terminal points of these two curves, corresponding to $\alpha = 12°$ and $15°$, respectively, fall within the scattering range of this correlation curve, and are thus, by the above postulation, the maximum allowable angle of attack prior to stall. This finding is entirely consistent with the observation made by Gault,[8] who stated that for higher angles of attack than the ones indicated above, depending on the Reynolds number, these airfoils either stalled or the flow became unsteady. In addition to these two examples, theoretical velocity distributions on the NACA 0012 airfoil at $\alpha = 7°$, $12°$, and $16.2°$ were also obtained. (The stalling of this airfoil belongs to the type of reseparation and was selected for correlation by Evans and Mort.) The prestall conditions of U_p/U_∞ and ΔS_l at $\alpha = 7°$ and $12°$ are shown in Fig. 4, which constitute curve (c). However, there are two points for every angle of attack; one from the "exact" numerical calculation with the Kutta condition imposed and the other from the modified numerical calculation with C_l matched with the measured value (see ref. 2 for explanation). The difference is seen to diminish as the angle of attack decreases. The case of $\alpha = 16.2°$, corresponding to the onset of stall, was also computed by the two methods; the results were, however, not plotted in Fig. 4, since our stalling peak velocity turned out to be somewhat higher than Evans and Mort's value ($U_p/U_\infty = 3.79$) and to plot it in the same diagram may result in unnecessary confusion. The discrepancy is believed to be due mainly to the different mode of relaxing the Kutta condition.

In addition to this characteristic of a prestalling curve, it is also worthwhile to notice two other features. The spread of this curve between different angles of attack is sufficiently large so that the major portion is outside the correlation scattering, and, moreover, this curve intersects the correlation curve at an angle of nearly 90°. If these features were not present, discernibility would be considerably reduced and application of the procedure would be difficult.

A word or two in regard to these two examples seems to be pertinent at this stage. As noted above, the measured pressure distributions were used, instead of the theoretical ones, to determine the required quantities U_p/U_∞ and ΔS_l. However, in view of the fact that the measured C_l for airfoils of this type increases almost linearly with α prior to stall, the difference between experiment and computation is expected to be minor until very close to the maximum lift where sudden departure occurs. The stalling above these terminal angles was reported to be abrupt for both airfoils. Since no plot of the lift coefficient versus the angle of attack was available, it remains unknown whether the stalling indeed satisfies the abruptness criterion. The boundary-layer Reynolds numbers for both cases were, however, calculated and found to be greater than the critical value of 370. Like the examples cited in Section II, the range of the freestream Reynolds number in the present experiments is also extremely narrow.

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