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TECHNICAL NOTE 3963

A CORRELATION OF LOW-SPEED, AIRFOIL-SECTION STALLING CHARACTERISTICS WITH REYNOLDS NUMBER AND AIRFOIL GEOMETRY

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Washington

March 1957

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A CORRELATION OF LOW-SPEED, AIRFOIL-SECTION STALLING CHARACTERISTICS WITH REYNOLDS NUMBER AND AIRFOIL GEOMETRY

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SUMMARY

The low-speed stalling characteristics of a large number of airfoil sections have been correlated with Reynolds number and a single airfoil ordinate near the leading edge as the correlating parameters. The correlation is appropriate only to airfoils without high-lift devices in flows of very low turbulence and with aerodynamically smooth surfaces.

INTRODUCTION

It is often of interest, from consideration of wing design and analysis of related aerodynamic data, to know the effects of variables such as Reynolds number and airfoil geometry on the low-speed stalling characteristics of airfoil sections. Toward this end, there is presented herein a correlation which has been devised between the stalling characteristics of airfoil sections and (as the independent variables) Reynolds number and a simple geometric measurement from an airfoil. The correlation is restricted to airfoils without high-lift devices and to airfoils with aerodynamically smooth surfaces. Experimental force and moment data for approximately 150 airfoils are employed to form the correlation and, in order to eliminate the influence of stream turbulence insofar as possible, the data are limited to measurements obtained in the two-dimensional, low-turbulence wind-tunnel facilities of the NACA (see ref.1).

GENERAL CONSIDERATIONS

Classification of Stall

Reference 2 describes three types of stall[1] for airfoil sections at low speed. The three types are:

[1]Reference 2 defines "stall" as the flow condition which follows the first lift-curve peak.

1. Trailing-edge stall (preceded by the movement of the point of turbulent boundary-layer separation forward from the trailing edge with increasing angle of attack).

2. Leading-edge stall (an abrupt flow separation of the laminar boundary layer near the leading edge, generally without subsequent flow reattachment).

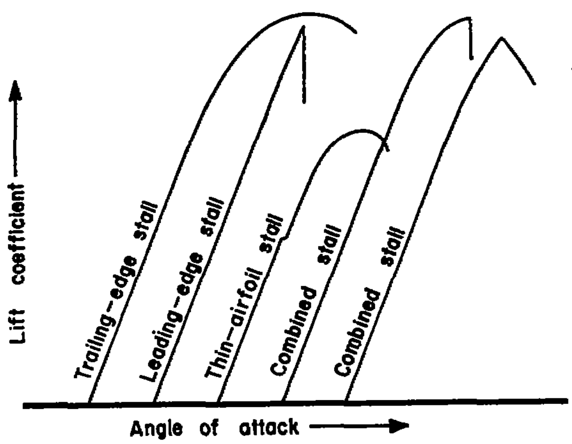
3. Thin-airfoil stall (preceded by flow separation from the leading edge with reattachment at a point along the chord which moves progressively downstream with increasing angle of attack).

It is inferred in reference 2 that the stall of any airfoil section can be described either by the characteristics of one of the types entirely or by a combination of the characteristics of two of the types. The correlation presented herein is based on this inference and considers four types of stall, the three "pure" types and a fourth type which, as discussed in reference 2, combines the characteristics of the trailing-edge and leading-edge stalls.

Sources of Data

References 1 and 3 to 13 present force and moment data for approximately 150 different airfoil sections over a range of Reynolds numbers from 0.7 to 25.0×10^6. All the data, as mentioned previously, were obtained in the two-dimensional, low-turbulence wind-tunnel facilities of the NACA. With the use of data for cambered airfoils at negative angles of attack (but restricting the data to airfoils without high-lift devices and to airfoils with aerodynamically smooth surfaces), the reference material provides force and moment variations for approximately 700 stalls (approximately 260 different airfoil shapes).

Procedure for Classifying Stalling Characteristics



Typical lift, drag, and pitching-moment variations (as well as boundary-layer and pressure-distribution measurements) are presented in reference 2 for each of the pure types of stall. These illustrative data served as standards for classifying the stalling characteristics of the airfoils in references 1 and 3 to 13 for the correlation. As shown in the accompanying sketch, the most significant characteristics for the various stalls were considered to be:

1. Trailing-edge stall - gradual and continuous force and moment variations and, in particular, a well-rounded lift-curve peak.

2. Leading-edge stall - little or no change in lift-curve slope prior to maximum lift and an abrupt, often large, decrease in lift after maximum lift is attained.

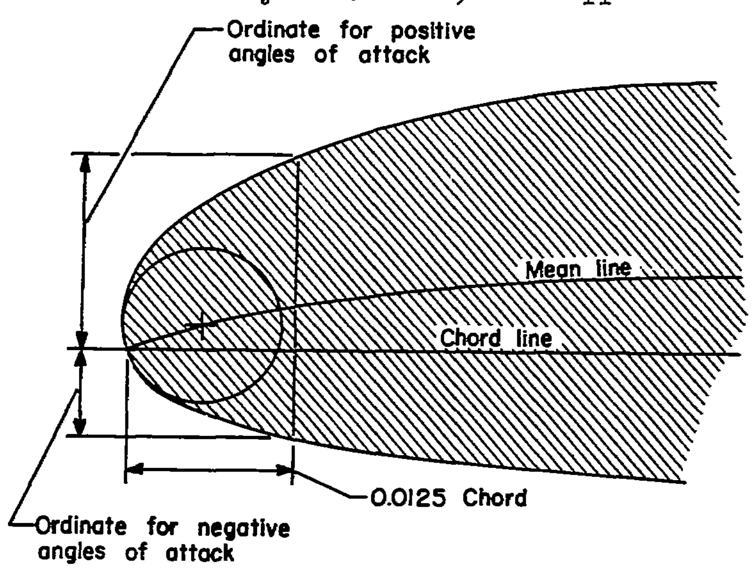
3. Thin-airfoil stall - a rounded lift-curve peak, generally preceded by a discontinuous force and moment variation for airfoils with a rounded leading edge (see discussion in ref. 2).

4. Combined trailing-edge and leading-edge stall - either a semirounded or relatively sharp lift-curve peak and followed by either an abrupt or relatively rapid decrease in lift (i.e., characteristics which are not typical for the first two pure types).

More detailed discussions of the force and moment variations for the stalls are given in reference 2.

Airfoil-Geometry Parameter Employed in Correlation

The geometric measurement from an airfoil section which is used to form the correlation presented herein is the upper-surface ordinate of an airfoil at the 0.0125-chord station, measured from the chord line as illustrated in the sketch. By definition, the "upper-surface" ordinate



for the stall of cambered airfoils at negative angles of attack is, of course, the lower-surface ordinate. Some degree of correlation is also possible with the use of other ordinates from between the 0.0075- and

0.05-chord stations. The 0.0125-chord-station ordinate was selected, however, because it is the standard-ordinate station which gives the most distinct correlation. Tabulated values of the 0.0125-chord-station ordinates for various NACA airfoils are presented as table I.

RESULTS AND DISCUSSION OF CORRELATION

The correlation of stalling characteristics is presented in figure 1. Due to the bulk of the measurements for Reynolds numbers of 3.0, 6.0, and 9.0×10^6 the symbols for these data have been scattered about about their respective values of Reynolds number for reasons of clarity. Although 3.6 is the maximum value shown in the figure for the upper-surface ordinate, there are eight airfoil sections from the reference material with larger values. These data have been omitted in order to permit the use of a large scale factor in the figure. The stalling characteristics of these airfoils are of the trailing-edge type with one exception. For positive angles of attack the NACA 23018 profile has an upper-surface ordinate of 4.09 but, in disagreement with the general correlation, seems to exhibit the characteristics of the combined type of stall (Reynolds numbers of 3.0, 6.0, and 9×10^6). In contrast, the stall for this airfoil section for negative angles of attack is in agreement with the correlation (ordinate, 1.83; Reynolds number, 6×10^6; combined type of stall). This inconsistent behavior is also true for the NACA 23012 and 23015 airfoil sections (note the leading-edge and combined type stalls shown in the figure for values of the ordinate of 2.67 and 3.34, respectively). These three NACA 230-series profiles are the only airfoil sections of those investigated whose stalling characteristics are considered to be definitely inconsistent with the general results of the correlation. It is possible, however, that the stalls of these airfoils were preceded by an extremely rapid forward progression of the position of turbulent boundary-layer separation (i.e., a trailing-edge type of stall) and as such would agree with the correlation. This being a possibility illustrates that the decisions as to the types of stall are arbitrary for some cases and uncertain for a few cases. The inconsistent results for the NACA 230-series of airfoils, therefore, serve to emphasize the limitations and qualitative nature of the analysis presented herein.

The boundaries between what are considered the three fundamental types of stall are reasonably distinct, particularly between the leading-edge and thin-airfoil types of stall which are inherent to the thinner airfoils of current interest and applications. The boundaries for the combined type of stall are also fairly well defined and, as might be expected, the region encompassed by its boundaries lies on both sides of the boundary which separates the leading-edge and trailing-edge types of stall. There are, therefore, five regions defined in figure 1: (1) a region for only the thin-airfoil stall; (2) a region for only the leading-edge stall; (3) a region in which both the leading-edge stall and the combined type of stall occur; (4) a region in which both the trailing-edge stall and the combined type of stall occur; and (5) a region for only the trailing-edge stall. The combined type of stall is, effectively, a transitional type which either may or may not occur when the thickness ratio of a given family of airfoils is decreased so that the type of stall changes from a trailing-edge to a leading-edge type of stall.

Some trends indicated by the results of the correlation shown in figure 1 are worth noting. For Reynolds numbers less than about 10^6 the data indicate that the leading-edge and combined types of stall do not occur and, moreover, the thin-airfoil stall tends to occur for thicker or more highly cambered airfoils as the Reynolds number decreases. This would seem to be a logical trend; any reduction in Reynolds number to very low values would tend to delay the occurrence of transition from laminar to turbulent flow in the boundary layer. This, in turn, should lead to more extensive regions of separated laminar flow which would favor the prominence of the thin-airfoil stall at the expense of the leading-edge stall. This line of reasoning suggests that an increase in the Reynolds number should hasten the occurrence of transition and should either preclude or greatly reduce any extents of separated laminar flow. This, in turn, would tend to eliminate or at least lessen the occurrences of leading-edge and thin-airfoil stall with the resultant predominance of the trailing-edge type of stall. The results in the figure are consistent with such reasoning for Reynolds numbers between 10^6 and 10^7; the available data for higher values of Reynolds number are meager, however, and the trends are by no means conclusive.

CONCLUDING REMARKS

Since the phenomena of stalling are inseparably related to the behavior of the boundary-layer flow, there is some physical basis for a correlation between stalling characteristics and Reynolds number. However, the relationship between stalling characteristics and an upper-surface ordinate near the leading edges of airfoils has no apparent physical significance. The degree of correlation obtained, therefore, is surprising and would seem to be a fortuitous result from strictly an empirical approach to the problem of stalling. In this connection it is to be emphasized that the decisions as to the types of stall were admittedly arbitrary for some cases and in a few cases uncertain. The principal justification for the correlation is its simplicity and the reasonable distinctness of the boundaries dividing the three pure types of stall.

Ames Aeronautical Laboratory
National Advisory Committee for Aeronautics
Moffett Field, Calif., Jan. 7, 1957

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TABLE I.- UPPER-SURFACE ORDINATES AT THE 0.0125-CHORD STATION FOR VARIOUS NACA AIRFOIL SECTIONS

NACA airfoil series	Thickness ratio, percent chord									
	0	6	8	9	10	12	15	18	21	24
00XX	0	0.95	1.26	1.42	1.58	1.89	2.37	2.84	3.31	3.95
24XX	.12	1.11	1.44	1.62	1.78	2.15	2.71	3.28	3.87	4.44
44XX	.25	1.25	---	1.81	---	2.44	3.07	3.76	4.45	5.20
230XX	.36	1.42	---	2.02	---	2.67	3.34	4.09	4.87	5.65
16-0XX	0	.65	---	.97	---	1.29	1.61	1.94	2.26	---
63-0XX	0	.77	---	1.15	1.27	1.52	1.88	2.22	2.53	---
63-2XX	.11	.89	---	1.29	1.41	1.69	2.08	2.46	2.78	---
63-4XX	.21	1.02	---	1.44	---	1.85	2.30	2.76	3.10	---
64-0XX	0	.75	1.01	1.13	1.25	1.49	1.84	2.18	2.52	---
64-2XX	.11	.88	1.14	1.26	1.40	1.65	2.03	2.49	2.77	---
64-4XX	.21	1.01	---	1.41	---	1.83	2.25	2.70	3.06	---
65-0XX	0	.72	.95	1.06	1.17	1.39	1.70	2.01	2.30	---
65-2XX	.11	.84	---	1.19	1.30	1.54	1.88	2.21	2.54	---
65-4XX	.21	.97	---	1.32	1.47	1.70	2.07	2.43	2.78	---
66-0XX	0	.69	.92	1.03	1.14	1.36	1.67	1.95	2.24	---
66-2XX	.11	.81	---	1.16	1.28	1.51	1.85	2.15	2.46	---
66-4XX	.21	.93	---	1.30	---	1.67	2.03	2.36	2.68	---
63A0XX	0	.75	1.00	---	1.25	1.49	1.84	---	---	---
64A0XX	0	.74	.98	---	1.23	1.46	1.81	---	---	---
65A0XX	0	.72	.95	---	1.18	1.41	1.75	---	---	---

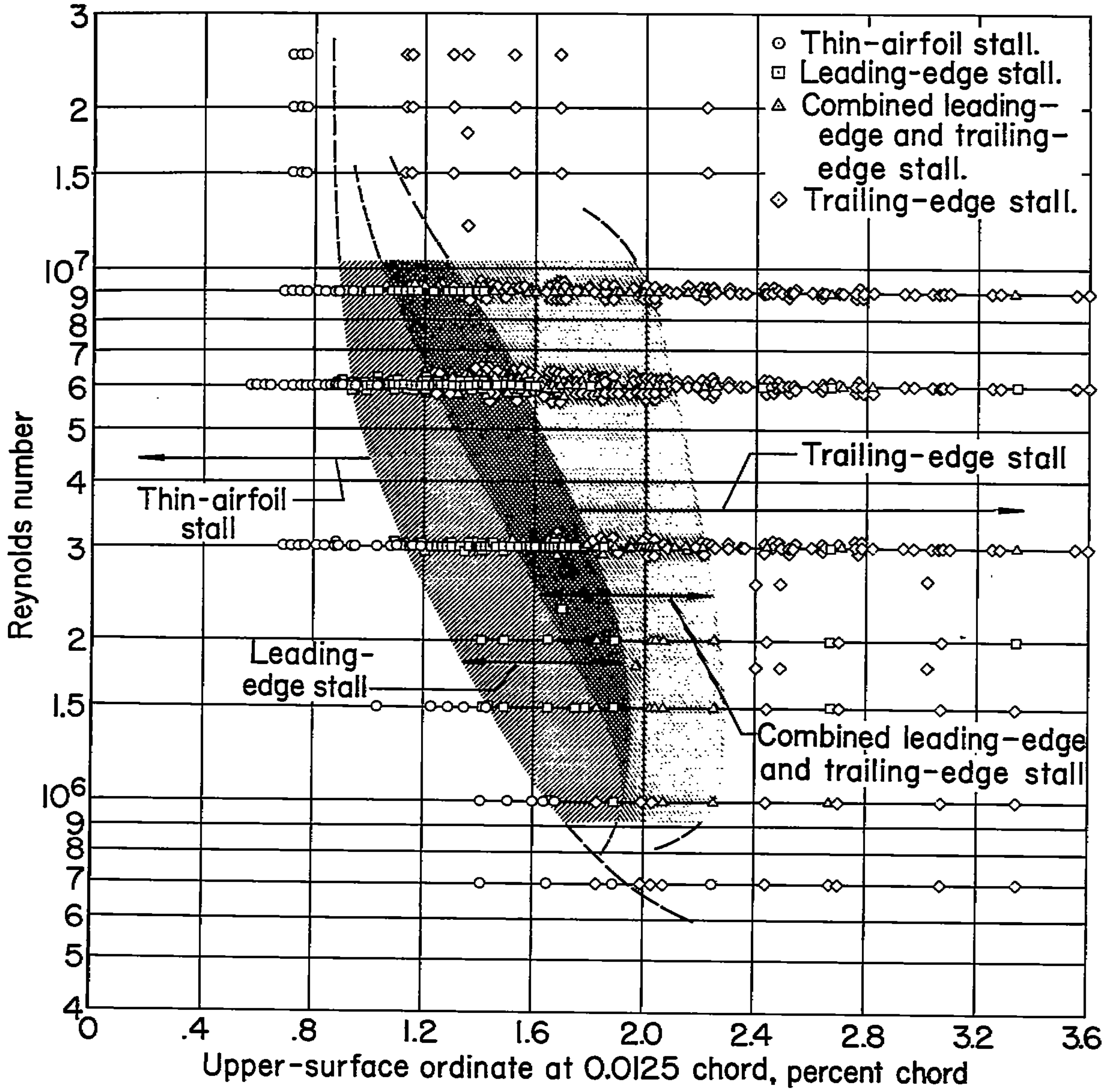

Figure 1.- The low-speed stalling characteristics of airfoil sections correlated with Reynolds number and the upper-surface ordinates of the airfoil sections at the 0.0125-chord station.