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Visualization of stall characteristics of airfoils using the smoke-wire technique

Wu, Tsung-Ju, M.S.
The University of Texas at Arlington, 1992
VISUALIZATION OF STALL CHARACTERISTICS OF AIRFOILS

USING THE SMOKE-WIRE TECHNIQUE

The members of the Committee approve the masters thesis of Tsung-Ju Wu

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VISUALIZATION OF STALL CHARACTERISTICS OF AIRFOILS
USING THE SMOKE-WIRE TECHNIQUE

by
TSUNG-JU WU

Presented to the Faculty of the Graduate School of
The University of Texas at Arlington in Partial Fulfillment
of the Requirements
for the Degree of

MASTER OF SCIENCE IN AEROSPACE ENGINEERING

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November 5, 1992
ABSTRACT

VISUALIZATION OF STALL CHARACTERISTICS OF AIRFOILS USING THE SMOKE-WIRE TECHNIQUE

Publication No._______

Tsung-Ju Wu, M.S.
The University of Texas at Arlington, 1992

Supervising Professor: Donald D. Seath

An experimental study is presented for the visualization of three types of stall characteristics, thin-airfoil stall, leading-edge stall, and trailing-edge stall, using the smoke-wire technique. Three airfoil sections, NACA 64-206, NACA 4412, and NACA 4421, were selected to obtain the thin-airfoil stall, leading-edge stall, and trailing-edge stall, respectively. The smoke-wire technique was developed to produce an appropriate amount of fine smoke filaments in the UT Arlington low-speed wind tunnel. The smoke filaments were used to visualize the flow around three airfoils that were pitched from zero incidence to the static stall angle. The experimental results were recorded by a still camera. Serial pictures showed the flow patterns around the pitching airfoils. Stall characteristics are described.
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NOMENCLATURE

V : velocity of the free stream.
Cₗ : lift coefficient.
Re : Reynolds number.
S : laminar separation point.
T : turbulent.
R : turbulent reattachment.
CHAPTER 1

INTRODUCTION

The use of smoke in wind tunnels has been developed into an important research tool in aerodynamics and become a field of increasing interest in recent years. The smoke-wire technique is known to be capable of producing fine smoke filaments for flow visualization and can be used to study the detailed structure of flow. T. J. Mueller and his co-workers used it to investigate the separation and transition on airfoils (Ref. 1) and flow structures of airfoils at low Reynolds number (Ref. 2). W. K. Chen used it to study the flow around a pitching airfoil (Ref. 3). This technique has been applied widely (Ref. 1).

The stall characteristics of a complete wing may be dependent on the factors of airfoil shape, wing plan form, wing twist, surface roughness, stream turbulence, and Reynolds number. The study of stall characteristics of airfoil sections is an important phase of the over-all wing stall and can help the airplane designer in selecting the airfoil sections. In this study, the smoke-wire technique was used in the U. T. Arlington low-speed wind tunnel for visualization of stall characteristics of airfoil sections. This wind tunnel is open circuit type, and is therefore suitable for applying the smoke-wire technique.
The purpose of this study is to summarize and support the theory of stall by flow visualization. Initially, this experiment was only focused on the smoke visualization of flow patterns of airfoils pitched at various angles of attack, but it was obvious that lift force characteristics of airfoils also had important effects for the stall detection. Therefore, a lift force measurement study was performed and results correlated with the flow visualization. The results of this experiment include the smoke visualization of stall, as well as the lift force measurements.

Three airfoil models, NACA 4421, NACA 4412, and NACA 64-206, were chosen for this experiment. They were used to obtain three different types of stall characteristics, trailing-edge stall, leading-edge stall, and thin-airfoil stall. Each of the models was pitched from zero incidence to its stall angle in the low-speed wind tunnel. Flow visualization photographs and lift force measurements were made while the models were pitched at various angles of attack.

The wind tunnel speed was set at approximate 13 ft/second for smoke visualization. For force measurements, the wind tunnel speed was set at approximately 13, 30, and 40 ft/second. Thus, force data were acquired at three different Reynolds numbers. A still camera was used to record the visualization results. Lift force measurements were made using a strain gauge balance system.
CHAPTER 2

STALL CHARACTERISTICS

Although the aerodynamic characteristics of an airfoil are dependent on the shape and the Reynolds number, the relationship between angle of attack and the lift coefficient, \( C_L \), is generally linear at moderate angles of attack. Fig. 1 shows the typical lift characteristics. As the angle of attack is increased, the lift coefficient increases smoothly until a maximum value is reached. Further increases in angle of attack will cause a decrease in \( C_L \). The airfoil is said to be stalled when \( C_L \) drops in this fashion.

![Graph showing typical lift characteristics](image)

Fig. 1 Typical lift characteristics
Near the stall, the relationship between $C_L$ and the angle of attack of airfoils and their stall characteristics are dependent on the thickness-chord ratio, the shape of upper surface near the leading edge, camber, and the Reynolds number (Ref. 4). Static stall behavior is generally divided into three types, thin-airfoil stall, leading-edge stall, and trailing-edge stall. Some airfoils change their stall type according to Reynolds numbers (Ref. 5).
2.1 Trailing-edge Stall

When the boundary layer separates from the surface at a certain angle of attack as a result of the adverse pressure gradient downstream of the point of minimum pressure. The separated shear layer is very unstable. Therefore, the flow will either remain separated, thereby producing an immediate change in the lift, or become turbulent and reattach to the surface. For the former, as the angle of attack increases, the separation moves toward the leading edge. This happens because the increase in the angle of attack results in an increased adverse pressure gradient. Therefore, the separation point will move closer to the leading edge. Finally, the separation region covers the entire upper surface, and then the airfoil stalls. This is referred to as trailing-edge stall.

This type of stall is characteristic of most thick airfoil sections. Airfoil sections with thickness-chord ratio greater than approximately 16 % generally have this type of stall (Ref. 6).
2.2 Leading-edge Stall (Short-bubble stall)

In some cases, after separation the flow transits from laminar to turbulent flow, and the turbulent shear stresses energize the shear layer by entraining fluid from the external stream causing the pressure to rise. Reattachment occurs when the pressure is almost equal to the value had there been a turbulent boundary layer without separation bubble on the airfoil (Ref. 7). The region between the points of separation and reattachment is known as a laminar separation bubble, shown in Fig. 2. The bubble extends over a distance which is primarily dependent on the shape of airfoil. Separation bubbles have been classified to two distinct types, long or short.

![Diagram of laminar separation and turbulent reattachment](image-url)

**Fig. 2** Laminar separation and turbulent reattachment
For the short bubble type, flow separates from the upper surface at a certain angle of attack, and reattaches to the surface leaving a small bubble. As the angle of attack increases, the bubble moves toward the leading edge, and becomes shorter in length. The separated shear layer becomes completely turbulent closer to the leading edge at high angles of attack. Further increase in angle of attack results in an increased adverse pressure gradient, thus requiring more energy for reattachment to occur. Therefore, the stall may be caused by either a breakdown of the small bubble near the leading edge due to failure of the separated flow to reattach, or downstream depletion of sustaining energy within the turbulent boundary layer (Ref. 8). The specific mechanism for bubble breakdown is not quite known. It has been postulated that there is a physical limitation in the amount of pressure recovery possible in the turbulent shear layer, so that the bubble bursts when the limit is exceeded and the shear layer fails to reattach (Ref. 9).

This type of stall is called leading-edge stall or short-bubble stall. Airfoil sections with medium thickness chord ratio, about 10 % to 16%, generally have this type of stall (Ref. 5).
2.3 Thin-airfoil Stall (Long-bubble stall)

It has been noted (Ref. 7) that at a certain Reynolds number, the turbulent mixing process and entraining process which follow the laminar separation can no longer increase pressure high enough for reattachment to occur and form a short bubble. Therefore, the turbulent shear layer reattaches much further downstream to form a long bubble. A long separation bubble usually occurs on a thin airfoil. Long separation bubbles exhibit a surface pressure distribution that has a smoother recovery to the unseparated turbulent boundary layer value.

For a thin airfoil, flow separates from the upper surface right behind the leading edge at a low angle of attack because of the sharp leading edge. If a long bubble forms at a certain angle of attack, its length will increase with increasing incidence. As further increase of incidence, the bubble will ultimately extend to the trailing edge or even downstream wake, and this condition results in effective stall of the airfoil. This type of stall is called thin-airfoil stall or long-bubble stall. Airfoil sections of thickness-chord ratio smaller than about 6 % without large camber generally have this type of stall (Ref. 5).
CHAPTER 3

EXPERIMENTAL APPARATUS AND TECHNIQUE

All the experiments were conducted in a low-speed wind tunnel in the Engineering Laboratory Building at University of Texas at Arlington. It is an open circuit, atmospheric exhaust type wind tunnel with a test section of 2.5-ft by 2.5-ft cross section. The top, front, and rear the test section are plate glass for facilitating flow visualization.

3.1 Airfoil Models and Drive Mechanism

Three wooden models were used in this study. In order to obtain three different types of stall, trailing-edge stall, leading-edge stall (short-bubble stall), and thin-airfoil stall (long-bubble stall), the profiles of the three airfoil models were NACA 4421, NACA 4412, and NACA 64-206, respectively (Ref.10). They were used for both smoke visualization and force measurements. Each model had a chord of 10 inches, and a span
Table 1 Specification of models

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<td>NACA 4412</td>
<td>NACA 64-206</td>
</tr>
<tr>
<td>chord length</td>
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<td>10 inches</td>
<td>10 inches</td>
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<tr>
<td>span</td>
<td>29 inches</td>
<td>29 inches</td>
<td>29 inches</td>
</tr>
<tr>
<td>thickness-chord ratio</td>
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<td>12 %</td>
<td>6 %</td>
</tr>
<tr>
<td>leading-edge radius</td>
<td>4.85 % chord</td>
<td>1.58 % chord</td>
<td>0.256 % chord</td>
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<tr>
<td>location of maximum thickness</td>
<td>30 % chord</td>
<td>30 % chord</td>
<td>40 % chord</td>
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Fig. 3  Test section setup

Fig. 4  Test section setup
of 29 inches. The details of three airfoil models are shown in Table. 1. These models were sprayed with flat black paint for smoke visualization. A spar that passed through the quarter-chord axis of each airfoil allowed the airfoil model standing vertically through a hole on the floor of the test section, shown on Fig. 3 and Fig. 4. One end of spar was mounted on the six-component balance system, AEROLAB Pyramidal Strain Gauge Balance System (Ref. 11). The angular position in angle of attack can be controlled by adjusting the Veede Root counter of the balance system (Fig. 5).

Fig. 5 AEROLAB strain gauge balance system
3.2 Force Measurement

In order to the support flow visualization and to get more insight of the stall characteristics, force measurement tests were conducted for the three airfoil models. The force measurements were made using a six-component strain gauge balance capable of measuring lift, drag, side force, pitching moment, yawing moment, and rolling moment. However, only lift force measurements were made in this experiment. Each airfoil model was pitched from zero incidence to its stall angle. The force data were then ensemble-averaged with at least four data sets for each different Reynolds number.

3.3 Smoke-wire Technique

The smoke-wire technique was used to visualize the stall characteristics. The method for smoke visualization was described by Chen (Ref. 3). A 0.00669-inch (0.17 mm) stainless steel wire was used for the whole experiment. The location of the smoke-wire is shown in Fig. 6. A variable transformer, POWERSTAT Variable Auto-transformer, was used as a power supply. This transformer can transform the input voltage of 120 V a.c.
to the output range of 0 to 140 V a.c. For safety and smell considerations, mineral oil was used as the coating oil to generate the smoke filaments.

Getting clear photographic records is the most important thing for flow visualization. The lighting used to illuminate the smoke filaments in the test section should be noted. Two 1000-Watt Berkey Colortran lights were used as the lighting for this experiment. The camera used for the photography was a Nikon N6006 with a 35-70 mm lens. Both Kodak Tri-x and T-max black-and-white films with 400 ASA were used. It is not necessary to use special methods to generate a plane of light normal to the camera, for example, the laser light method (Ref. 12). But in order to minimize the glare from the lights, the arrangement of the lights and the camera is shown in Fig. 6.

For taking good pictures of smoke visualization, high shutter speed of camera is necessary. Low shutter speed will the smokelines foggy. A shutter of 1/1000 second was used for the whole experiment. For this high shutter speed, the light must be strong enough to expose the film. In order to avoid the strong heat coming from the lights harming the wind tunnel and models, some control switches were used to synchornize the camera and lights. The two 1000 Watt lights and the camera shutter were triggered synchronously. The camera shot while each model was pitched at various angle, then flow visualization results were made.
Fig. 6 Wire, camera, and light location
CHAPTER 4

DISCUSSION OF RESULTS

4.1 Force Measurement Results

For lift force measurements, the wind tunnel speed was set to be approximate 13, 30, and 40 ft./second. Thus the corresponding Reynolds numbers were about 68000, 158000, and 210000. Force data were acquired while the airfoils were pitched at various angles of attack. This resulted in a series of lift coefficient curves for the measured airfoils at various angles of attack. Figs. 7-9 show the plots of the results.

Trailing-edge stall

Fig. 7 shows the lift coefficient curves of NACA 4421 airfoil at three different Reynolds numbers. For the first Reynolds number, 68000, the stall angle is 19 degrees. The stall angles for the second Reynolds number, 158000, and the third Reynolds number, 210000, are 21 degrees and 22 degrees,
Fig. 7  Lift coefficient of NACA 4421
respectively. The lift characteristic shows smooth and continuous variations from zero to stall. The peaks of the lift curves are rounded, and the loss of lift after stall is gradual. Before about 9 degrees, the lift coefficient increases almost linearly. After about 9 degrees, the slope of lift coefficient changes with increasing angle of attack.

Leading-edge stall

Fig. 8 shows the lift coefficient of NACA 4412 airfoil. The stall angle is 15 degrees at the Reynolds number of 68000. For the Reynolds numbers of 158000 and 210000, the stall angles are the same, 16 degrees. The lift characteristic shows abrupt discontinuity when the angle of attack for maximum lift is exceeded. There is but little or no rounding over of the lift coefficient curves near maximum lift, and the peaks of the curves are sharp. The lift coefficient increases almost linearly before maximum lift is reached. The discontinuity of lift coefficient could be caused by the breakdown of the separation bubble. However, sufficient increase in angle of attack eventually moves laminar separation so far forward that the separated flow does not reattach to the surface after transition occurs. Maximum lift has then been obtained. The
Fig. 8 Lift coefficient of NACA 4412
maximum lift of this airfoil is higher than that of the other two airfoils. The lift coefficient after stall is quite different from those of the other two types. It is characterized by an abrupt loss in lift after stall, whereas the loss of lift of the other two types is gradual after stall.

Thin-airfoil stall

Fig. 9 shows the lift coefficient of NACA 64-206 airfoil. At Reynolds number of 68000 the stall angle is 12 degrees. For Reynolds numbers of 158000 and 210000 the stall angle is 13 degrees. The top of the curve is relatively flat. Sometime, there is no distinct maximum lift coefficient on the curve. For NACA 64-206 airfoil, there is only little loss of lift after the stall. It is not so easy to detect the stall of NACA 64-206 airfoil as that of the other two airfoils. Maximum lift is reached when the separation bubble covers the entire upper surface at a certain angle of attack. Further increase of angle of attack will cause the separation bubble to extend to downstream wake region, and the lift coefficient to gently decrease.
Fig. 9 Lift coefficient of NACA 64-206
Summary

The preceding results of lift force measurement show that when the Reynolds number is higher, the stall angle is also higher. This may be explained as follows. When the flow is at low Reynolds number, i.e., low speed, there is not enough energy in the flow to overcome the adverse pressure gradient on the upper surface of an airfoil. As the Reynolds number is increased, i.e., the velocity is increased, the energy of the flow is also increased until sufficient energy exists such that the flow can negotiate the adverse pressure gradient on the airfoil. Thus the flow may remain attached on the upper surface at certain angle of attack which flow has already separated at lower Reynolds number. Therefore, stall angles for the three airfoils are increased as the Reynolds numbers on the airfoils are increased.

4.2 Flow Visualization Results

It should be noted that there was some limit in the wind tunnel speed for applying the smoke-wire technique (Ref. 3). The smoke wire is like a circular cylinder in the flow field.
When the flow speed increases, the wake of the wire will change from unseparated flow to fixed vortex pair, even to laminar vortex street. After the wake becomes vortex street, the wire would generate broken smoke filaments. These broken filaments were not suitable for flow visualization. According to the test results, it showed that when the wind tunnel speed was over 14 ft./second, the smoke filaments began to be broken. Therefore, the wind tunnel speed was set to be about 13 ft./second for flow visualization. The corresponding Reynolds number, Re, based on the 10-in chord was about 68000. The photography was taken, while each airfoil model was pitching from zero angle of attack to its static stall angle. Series pictures show the flow pattern around each airfoil model at various angles of attack.

Trailing-edge stall

The example of trailing-edge stall was provided by the NACA 4421 airfoil section. Figs. 10-13 show the results. In this type of stall, flow separation on the upper surface starts at the trailing edge. The laminar boundary layer separates near the trailing edge, and never reattaches. In Fig. 10 the airfoil had a moderate angle of attack, and some amount of separation near the trailing edge can be seen by the outward displacement
of the streamline from the upper surface. As the angle of attack of the airfoil was increased, the separation region progressed toward the leading edge, and became longer in its length (Fig. 11). Fig. 12 shows the separation region covering about 80% of chord of the airfoil. Finally, in Fig. 13, the separation region covered nearly the entire upper surface of the airfoil indicating that the airfoil was stalled.

These pictures indicate that this type of stall results from separation moving progressively forward from the trailing edge with increasing angle of attack. Throughout the range of moderate and high angles of attack the forward progression of separation is gradual and continuous.
Fig. 10  NACA 4421 airfoil at angle of attack of 5 degrees and Reynolds number of 68000. The separation started at about 75% chord.

Fig. 11  NACA 4421 airfoil at angle of attack of 10 degrees and Reynolds number of 68000. The separation started at about 65% chord.
Fig. 12 NACA 4421 airfoil at angle of attack of 16 degrees and Reynolds number of 68000. The separation started at about 15% chord.

Fig. 13 NACA 4421 airfoil at angle of attack of 19 degrees and Reynolds of 68000. The separation is near the leading edge.
Leading-edge stall

The example of leading-edge stall (short-bubble stall) was furnished by the NACA 4412 airfoil. Figs. 14-20 show the short bubble stall. Fig. 14 and Fig. 15 show that NACA 4412 airfoil was at low angles of attack. There was no separation bubble near the leading edge, but a separation region was formed near the trailing edge (Fig. 14). As the angle of attack increased, the separation region moved upstream (Fig. 15). At a high angle of attack the separation bubble is quite apparent as shown in Figs. 16 and 17. Fig. 16, taken at angle of attack of about 12 degrees, shows the laminar separation just behind the leading edge and the turbulent reattachment. Fig. 17 is an enlargement of Fig. 16. As the angle of attack continuously increased a little, the turbulent reattachment moved upstream and the separation bubble shrank (Fig. 18). Comparing Fig. 16 with Fig. 18, the separation bubble in Fig. 18 is smaller than that in Fig. 16. Further increase of angle of attack caused the airfoil to stall, as shown in Fig. 20, resulting in a sudden decrease in lift coefficient. This stall may be caused by upstream movement of the rear turbulent separation point as described in trailing edge stall, or by the breakdown of the small bubble.
Fig. 14  NACA 4412 airfoil at angle of attack of 4 degrees and Reynolds number of 68000. The rear separation started at about 80% chord.

Fig. 15  NACA 4412 airfoil at angle of attack of 7 degrees and Reynolds number of 68000. The rear separation started at about 70% chord.
Fig. 16 NACA 4412 airfoil at angle of attack of 12 degrees and Reynolds number of 68000. Flow separated near the leading edge and reattached at about 20% chord.

Fig. 17 NACA 4412 airfoil at angle of attack of 12 degrees and Reynolds number of 68000. Fig. 17 is an enlargement of Fig. 16.
Fig. 18  NACA 4412 airfoil at angle of attack of 14 degrees and Reynolds number of 68000. The reattachment is located at about 15% chord.

Fig. 19  NACA 4412 airfoil at angle of attack of 14 degrees and Reynolds number of 68000. Fig. 19 is an enlargement of Fig. 18.
Fig. 20  NACA 4412 airfoil at angle of attack of 17 degrees and Reynolds number of 68000. The airfoil is stalled.
Thin-airfoil stall

Figs. 21-26 show the thin-airfoil stall (long-bubble stall). At angle of attack of about 0 degree, flow passed the airfoil without separation, shown in Fig. 21. Because of the sharp leading edge, flow separated from the upper surface at the leading edge at a very low angle of attack, and reattached downstream on the surface forming a small bubble, (Fig. 22). As the angle of attack increased, the turbulent reattachment point moved aft, then the bubble grew and increased its length. Fig. 24 shows the separation bubble covering half the chord length. At a higher angle of attack, the separation bubble covered almost the entire chord, and maximum lift was reached, as shown in Fig. 25. In Fig. 26, the separation region extended into the wake downstream, and failed to reattach on the airfoil. The airfoil was stalled.

Both thin-airfoil stall and leading-edge stall are caused by the "breakdown" of the separation bubble. The distinct difference of these two types of stall is that the bubble grows before stall occurs with continuous increase in angle of attack for the former, whereas the bubble shrinks then bursts with increase incidence for the latter.
Fig. 21  NACA 64-206 airfoil at angle of attack of 0 degrees and Reynolds number of 68000. Flow passed the airfoil without separation.

Fig. 22  NACA 64-206 airfoil at angle of attack of 5 degrees and Reynolds number of 68000. Flow separated at the leading edge and reattached at about 20% chord.
Fig. 23  NACA 64-206 airfoil at angle of attack of 7 degrees and Reynolds number of 68000. The reattachment is located at about 30% chord.

Fig. 24  NACA 64-206 airfoil at angle of attack of 9 degrees and Reynolds number of 68000. The separation covered about half the chord.
Fig. 25 NACA 64-206 airfoil at angle of attack of 12 degrees and Reynolds number of 68000. The separation covered almost the entire chord.

Fig. 26 NACA 64-206 airfoil at angle of attack of 14 degrees and Reynolds number of 68000. The airfoil is stalled.
CHAPTER 5

CONCLUSIONS

The smoke-wire technique was used for flow visualization in the UT Arlington low-speed wind tunnel. In this study, the smoke-wire technique and associated equipment were described. The present results have demonstrated that the smoke-wire technique has a valuable visualization capability for the complex flow phenomena. Although stall characteristics have been of interest since many years before, the combination of visual and other measurement techniques in this study provided a means of improving our understanding of stall behaviors.

With the application of smoke-wire technique, the flow patterns around three airfoil sections at various angles of attack were visualized. From the preceding sections the three types of separated flows and stall characteristics were discussed. The trailing-edge stall is caused by upstream movement of the separation point from the trailing edge. The leading-edge stall results from the sudden breakdown of separation bubble or separation of the turbulent boundary layer just downstream of reattachment. The thin-airfoil stall is attributed to that the separation region, starting right after the leading edge, extends into the wake downstream, and fails to
reattach to the upper surface of an airfoil.

The regions of separated flow which form on airfoils govern the stall characteristics. The nature and extent of these regions are determined primarily by the airfoil shape, the Reynolds number, and the angle of attack. Therefore, the airfoil shape plays a very important role in determining the type of stall.
REFERENCES


