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SOME ASPECTS OF THE STALLING OF MODERN LOW-WING MONOPLANES

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SUMMARY

The factors affecting the stalling characteristics
of modern airplanes are briefly discussed. The effect
of present-day design trends is shown and means for im-
proving the stalling characteristics of future airplanes
are indicated.

INTRODUCTION

Stalling has always been one of the most important
problems relating to safety, and research on the subject
is continually being conducted. The problem has gained
particular prominence at the present time because of the
reputedly insidious and dangerous stalling characteristics
being exhibited by some modern airplanes, particularly
those of the low-wing type. It is the purpose of this
paper to discuss the known facts concerning stalling and
its dependence on the geometric arrangement of the air-
planes as an indication of what can be done to ameliorate
the present unsatisfactory situation.

All types of airplanes, the older as well as the
modern, lose their rolling stability at some angle of at-
tack. When this loss occurs, the airplane rolls into a
spiral dive from which recovery can be effected only by
reduction of the angle of attack, obtained by nosing down
the airplane still farther. Considerable height is lost
in the recovery so that the immediate danger depends on
the altitude at which the loss occurs. The maneuver is,
however, the classical "incipient spin" which, if permit-
ted to persist, becomes a fully developed spin from which
there may be no recovery. The presence of this unstable
condition near maximum lift constitutes one of the great-
est dangers attached to stalling. To the pilot the prac-
tical definition of the stall has always been the minimum

speed at which the airplane can be steadily flown in con-
trast to the technical definition, which defines stall on
the basis of the occurrence of the possible minimum speed
based on maximum lift regardless of the stability charac-
teristics. The two definitions may differ because roll-
ing instability, although associated with the occurrence
of maximum lift, may occur either before, simultaneously
with, or after the angle of maximum lift for the complete
airplane, or in all three ways at different times on the
same airplane, depending on several variables to be dis-
cussed.

Basically, the solution of the stalling problem con-
sists of the complete elimination of the rolling insta-
bility. This solution does not appear possible with ef-
ficient low-drag airfoils. For the time being at least,
the presence of the rolling instability must be accepted
and the problem must be considered as one of arranging
the airplane so that the probability of any pilot's ap-
proaching the angle of attack at which the unstable con-
dition occurs is as remote as possible. The present un-
satisfactory situation has arisen from the fact that the
attempts to clean up airplanes and to increase their ef-
ficiency have resulted in the development of a type that
not only tends to suppress all phenomena upon which the
pilot formerly depended to warn him of the possible loss
of the rolling stability but also tends to promote its
early occurrence. Thus, inadvertent stalling has become
increasingly associated with modern airplanes; and these
airplanes, because of their general arrangement and high
wing loadings, tend to behave worse when they are stalled.

STALL-APPROACH WARNINGS

It is essential that the pilot should in some manner
be forewarned of the approach of the stall, particularly
in the event that the airplane does exhibit such violent
rolling characteristics as have been lately experienced.
With older airplanes, say those of 5 or 10 years ago,
pilots were warned of the approaching loss of rolling
stability, and thus of lateral control, by a combination
of the following factors:

1. The speed indication given by the air-speed meter.

2. The nature of the vibration of the airplane and the changes in sound as affected by the propeller, the engine, and the airplane structure.

3. The deterioration of the lateral control and the large variation of elevator force and position as the air speed was reduced and the stall approached.

4. To some extent, the attitude of the airplane, particularly in the full-throttle condition.

Then, as now, the pilot had no direct indication of the angle of attack, which is the real basis for all stalling.

One investigator of this subject, Dr. H. J. van der Maas, has attached relative importance to the nature of warnings by classifying them as "passive" and "active." The air speed is a passive warning; the attitude of the airplane and the deterioration of the aileron and rudder control are passive in that they require the pilot's attention, but they are considerably more active than indications of the air-speed meter. The other warnings, that is, the nature of the vibration and the feel and location of the elevator control, are distinctly active because by their very nature they attract the pilot's attention. Active warnings are, of course, the most desirable. The general characteristics of the modern low-wing airplane are such that they tend to suppress all of these warnings with the exception of the reading of the air-speed meter and the change of attitude. The air-speed indication, aside from being only a passive warning, may also be somewhat misleading should the pilot not appreciate the fact that the stalling speed depends upon the normal acceleration existing. For instance, it is recognized that, inasmuch as the lift must be increased at a given air speed in a turn, the angle of attack is therefore increased over that required for the same air speed in level flight. The maximum lift obtained in a turn must be reached at a higher speed than that necessary for the same lift in level flight. A feasible, but not a particularly satisfactory or practical, means of reducing the possibility of a pilot's being misled by the air speed is to mark the dial with the stalling speeds for various normal accelerations and to use the instrument in conjunction with a sensitive indicating accelerometer;

the air-speed indication, however, would still remain a
passive warning. The attitude of the airplane is not
particularly useful as a warning except in unaccelerated
power-on flight.

CHARACTERISTICS OF AIRPLANE ARRANGEMENTS

AFFECTING THE STALL

The manner in which the present trend to aerodynami-
cally clean low-wing monoplanes with highly tapered wings
has acted to reduce the stall warnings is best shown by a
consideration of the factors upon which the stall warnings
depend. These factors are:

1. The wing-stalling characteristics, which influ-
      ence not only the stall warnings but also
      the violence of the motion following the
      stall.

2. The longitudinal-stability characteristics as
      they affect the elevator force and position.

3. The power loading and the L/D variation with
      angle of attack.

4. The regulation of the engine and propeller speed
      by the use of automatic mixture controls and
      constant-speed propellers.

Wing-Stalling Characteristics

The wing-stalling characteristics are important be-
cause upon them depends the vibration, or lack of it, in
the airplane structure and, to some extent, the variation
of elevator force and position at low speed. These fac-
tors are, of course, also affected by the position of the
tail. It is necessary, and generally the case, that the
tail position be designed to fall within the wing wake.
Vibration usually occurs when the flow breaks down at the
center section of the wing and results from the passage
of the turbulent-flow produced over the after portion of
the wing, the fuselage, and particularly the tail. The
problem of obtaining an appreciable vibration of the air-

plane consists in making the center section of the wing stall before the setting in of rolling instability, which accompanies the stall of the complete wing or wing tips. The elevator force and position are affected because a center-section stall is accompanied by a change in the flow over the tail. The downwash is decreased and, depending on tail position, the velocity may be either increased or decreased. The downwash reduction is equivalent to an increase in the longitudinal stability. If the load on the tail is downward, a decrease in the velocity over the tail has the same effect as the reduction of downwash, whereas an increase in the velocity is equivalent to a reduction in the longitudinal stability. Progressive loss of aileron control is also associated with a progressive center-section stall.

The wing-stalling characteristics depend upon a considerable number of factors, not all of which are clearly understood. The more important factors appear to be:

1. The wing plan form.

2. The wing twist.

3. The characteristics of the particular airfoil
    sections composing the wing.

4. The local interference and the propeller slip-
    stream.

The variables of the plan form are: wing taper, sweepback, and sweepforward. Sweepback appears to have some tendency to promote stalling at the tips prior to stalling at the center section, whereas sweepforward seems to have the reverse effect. These effects, however, appear to be secondary with respect to that of taper. Taper tends to produce higher angles of attack at the tips than at the roots of the wing. Since the local stall depends upon the local angle of attack and not upon the geometric angle of the wing as a whole, the result is that, for a tapered wing with no twist, a premature stall of the tips is promoted. That the effect may be very great is illustrated by the extreme case of a diamond-shape wing, for which theory indicates that the tips will be stalled for all angles of attack except the angle for zero lift. The area at the tips in this particular case is small so that such a wing will not necessarily have rolling instability

at all angles; but rolling instability will occur con-
siderably before the angle of maximum lift.

The obvious method of producing a center-section
stall is to arrange the wing so as to assure that the
tip sections have an effective angle of attack such as
required for them to stall last. One means of obtaining
such assurance is to wash out the incidence of the wing
tips. This method can be used, however, only where a
small decrease in the incidence of the wing tip is re-
quired, as in the case of a moderately tapered wing. A
large amount of wing twist, such as would be required for
a highly tapered wing, is undesirable because it tends to
increase the wing drag at high speeds and may destroy the
lateral stability of the airplane in that range.

Another means of assuring that the wing tips will
stall later than the center section consists in the use
of airfoil sections at the wing tip that reach their max-
imum lift at an appreciably higher angle of attack than
those of the wing root. Thus the benefit derived from
leading-edge tip slots, which increase the local stalling
incidence by the order of 10°, is obvious. The stall-
control flap also works on this principle. In this case,
however, the angular difference between the stall of the
wing tip and of the root is obtained by deforming the
root sections so as to decrease the angle of attack at
which they reach maximum lift and stall. The stall-con-
trol flaps do not seem to offer a particularly good so-
lution because they may not take full advantage of the
lifting capabilities of the wing and because of mechani-
cal difficulties, particularly in connection with auto-
matic operation.

The automatic wing-tip slots appear to offer much
better possibilities. They have a disadvantage, however,
in that it is difficult to obtain good slot opening and
closing characteristics without increasing the wing drag.
Fixed wing-tip slots are another possibility. These
slots eliminate the mechanical features of both the auto-
matic slots and the stall-control flaps but will increase
the drag. As they need be installed only in front of the
tip section, which is a relatively small part of the en-
tire wing span and area, the drag increase caused by them
may be justifiable.

Interferences to the flow tend to produce local

breakdowns. Thus, interference effects at the wing roots
will tend to produce a stall at those points and counter-
act the effects of taper. The modern practice of care-
fully filleting the wing-fuselage and wing-engine-nacelle
junctures and of suppressing all protuberances, such as
gas-tank and oil-tank caps and wing-root fittings, has
tended to eliminate interference effects. The occurence
of center-section stalls on modern airplanes with high
taper ratios simply indicates that, in specific cases,
fillets may not completely eliminate the effects of fu-
selage interference. Fortunate as this condition may be,
such specific cases should not be used in making general-
izations. The indications are that all airplanes with
highly tapered wings tend to stall in the manner indicat-
ed by classical wind-tunnel tests of similarly tapered
airfoils alone.

Sharp leading edges at the wing roots have been used
to interfere with the flow. The use of these sharp lead-
ing-edge pieces is advantageous in that they can be ap-
plied to existing airplanes and can be adjusted relative-
ly easily to give the desired degree of turbulence and
tail vibration.

The propeller slipstream has the effect of reducing
the interference. It complicates the problem of produc-
ing satisfactory stalling characteristics because the ef-
fects are not constant, are large, and are dependent on
throttle setting. Wing arrangements that may give satis-
factory stall warning, power on, may cause a destructive
tail "shake," power off. Conversely and more usually,
vibration that produces a warning, power off, may disap-
pear when the throttle is open.

LONGITUDINAL-STABILITY CHARACTERISTICS

The static longitudinal-stability characteristics
are important because they determine the variation of the
stick force and position with speed. With zero stability,
the speed of the airplane may change without any change
of stick position or control force. Thus, though the pi-
lot holds the stick steady, he has no assurance that the
speed may not decrease and that the airplane may not be
inadvertently stalled during presumably steady flight. A
high degree of stability causes large variations of stick

force and position with speed. These factors cannot be
inadvertently overlooked and, when the stick is freed
the airplane will return to the original flight speed.
The pilot may therefore always check back on his speed
simply by permitting the stick some freedom.

In addition to the conditions for straight flight,
the possibility of an inadvertent stall in a turn is
less for a stable airplane than that for an airplane
with zero stability. Inasmuch as the condition for zero
stick force is a function of angle of attack of the air-
plane and not of the airplane speed, the speed for zero
stick force, when a stable airplane is put into a turn,
will increase with the angle of bank in such a ratio
that the airplane will be no nearer the stall in the
turn than it was in the original steady-flight condition.
Even though the stable airplane were not balanced for
zero stick force and even though it were necessary to
hold back on the stick, if the same stick force be main-
tained in the turn, the speed would increase as it would
in the case of zero stick force; whereas, if an attempt
be made to maintain the same speed, the force would in-
crease - the amount depending on the degree of stability.

Most of the earlier airplanes were biplanes that,
happily, had desirable stability characteristics. With
these airplanes it was necessary, as the speed was re-
duced, to exert increasing moments by means of the ele-
vator, which accounted for the increase in stick force
and the increase in travel necessary to trim at lower
speeds. Development, when it originally led away from
biplanes, went to high-wing monoplanes, which have as
good inherent stability characteristics as biplanes. The
variation of stick force and position characteristic of
the high-wing type may be attributed, to a great extent,
to the relation between the vertical positions of the
center of gravity and of the center of effort, or the
aerodynamic center of the wing. It can readily be shown
that the stability of a biplane is more or less constant
with speed. With the high-wing monoplanes, the stability
is inherently greater at high angles of attack and low
speeds than at high speeds. This characteristic is par-
ticularly desirable in that it gives a large variation
of stick force and travel at the lower speeds without
making the airplane particularly stiff at high speeds.

Commander W. S. Diehl in a discussion of the problem
suggested another characteristic of the earlier airplanes

that probably helps to account for their favorable stick-
force characteristics. He pointed out that, with the
slower airplane in the days before flutter became a prob-
lem, the elevators were not mass balanced and required a
fairly large stick force simply to overcome the weight
moment. As the ratio between the aerodynamic and the
weight forces on the elevator decreases with speed, it is
obvious that the weight results in an apparent increase in
the variation of elevator pull required to lower the
speed.

It can be theroetically shown that the variation of
stability with speed for the low-wing airplane is oppo-
site that for the high-wing airplane. With the low-wing
airplane, the stability decreases as the speed is de-
creased. In general, the designer must lay out the air-
plane for the more usual cruising condition of flight and,
regardless of the wing arrangement, he attempts to obtain
the most desirable characteristics in this condition of
flight. For a given degree of stability at cruising
speed, the low wing therefore has an inherent disadvan-
tage over the other wing arrangements in that very small
stick-force variation will be obtained in the vicinity
of the stall. Added to these adverse effects of the low-
wing position used in modern airplanes is the reduction
of the elevator weight moment due to mass balancing of
the elevators.

Power Loading and Variation of L/D

Power loading and the variation of L/D with angle
of attack determine the attitude of the airplane when the
stall is approached for both the power-on and the power-
off conditions. A low power loading and a high L/D
produce a large angle of climb and consequently a steep
nose-up attitude, power on. Because of the abnormal at-
titude, there is not much danger of unforeseen stalling.
Flaps decrease the nose-up attitude by reducing the L/D.
With power off, the attitude of the airplane usually con-
tinues to change in a nose-up direction as the speed is
reduced almost to the stall even though the flight path
is steepening and the angle of attack is increasing. The
actual attitudes depend on whether the flaps are up or
down. When interference effects cause high drags prior
to the stall, the nosing over that occurs just prior to
the stall is accentuated, giving the pilot an additional
warning.

Regulation of Engine and Propeller Speed

The regulation of engine speed resulting from the use of constant-speed propellers and automatic mixture controls has eliminated much of the warning the pilot formerly obtained from the variation of engine propeller noise and vibration with speed. Furthermore, the action of the constant-speed propeller itself tends to mask any malfunctioning of the engines that might reduce the power being taken from them. This disadvantage, while applicable for only small decreases in power, reduces the dependency that may be placed on the attitude of the airplane as a stall warning.

When constant-speed propellers are further developed to cover a 90° range of angles, it may be possible that another source of danger to modern airplanes will be introduced when the automatic pilot is used in conjunction with the other automatic features. In level flight at cruising speed, the airplane has a definite angle that the automatic pilot tries to maintain. If the engine loses power, the nose tends to drop. The automatic pilot will try to bring the nose up to the original position, thereby increasing the angle of attack and decreasing the speed. With serious loss of power, it is possible for the automatic pilot to stall the airplane.

Miscellaneous Effects

Some cases have been observed with modern airplanes where the lateral-stability characteristics of the airplane tend to promote a premature stall. The first example of this premature stall is related to the low-wing position and the high wing loadings of modern airplanes, particularly small airplanes of the pursuit category. It has been known for a considerable time that the effective dihedral of a wing depends only partly on the geometric dihedral angle; it is also affected by interference effects set up by the fuselage. In general, the high-wing position tends to give a dihedral effect greater than that indicated by the actual dihedral angle. The low-wing position has the reverse effect and reduces the actual dihedral below that indicated by the wing angle. The magnitude of the effects depends upon the relative sizes of the fuselage and the wing; hence the effect is greatest on the very highly loaded pursuit airplanes.

For an airplane exhibiting negative dihedral effect, any use of the rudder, or for that matter any gust, that starts a skid will cause the advancing wing to drop instead of rise. This drop will result in an effective outward roll, which will increase the angle of attack of the downgoing wing. Then with the normal relations, this outward rolling will generate a yawing moment that will tend to add to the rudder yawing moment. The effects are therefore additive. When skidding occurs at slow speeds, the roll may be continued to the point where the advancing wing tip may stall.

Flaps and landing-gear position also appear to have some influence on the effective dihedral angle, but the extent of the influence is not known at present. In this connection it should be noted that skidding does not usually occur to any extent without the use of the rudder in flight. With one airplane in particular it has been observed that, although the airplane did not have a negative dihedral effect with rudder neutral, the side force on the rudder, coupled with the high rudder position, was sufficient to produce a rolling moment that counteracted the wing rolling moment so that any sideslipping the pilot performed in approaching for a landing usually resulted in a further lowering of the already low wing and the possibility of a premature stall.

In addition, for airplanes equipped with flaps, it has been observed that, as the stall is approached, the rudder effectiveness is apparently lost so that, if a wing drops, it may be impossible to return it to neutral or to prevent turning in the direction of the lowered wing by use of the rudder. When the ailerons are effective, the condition is not particularly dangerous if recognized. The condition is common to most airplanes with flaps and requires further study. A brief consideration of the condition in the light of existing stability theory indicates that it might be a natural consequence of the high lift and the low L/D of the normal flapped wing. The theory shows that, as the lift coefficient is increased, spiral stability becomes increasingly difficult to obtain and that the motions resulting from spiral instability become increasingly violent. Also, if the spiral is permitted to develop until the wing rolls from the level condition by a certain amount, the inherent yawing moments become greater than the counteracting moments that can be applied with the rudder. If the angle

of bank is exceeded for any reason, say because of a gust
or an aileron movement, the same conditions probably apply.

The problem is further complicated by the fact that
the flap "shadow," or wake, may blanket the vertical sur-
faces at low speeds, thus reducing the directional weath-
ercock stability and rudder effectiveness. With small
highly loaded airplanes, there may be an additional blan-
keting of one-half the stabilizer when sideslip sets in.
This effect is probably more pronounced when flaps pro-
ducing high lift, and consequently large downwash, are in
operation. When the speed of these airplanes is decreased
to the minimu, one wing will drop violently. Simultane-
ously with the wing drop, the change of air flow over the
tail relieves the load on the tail sufficiently to permit
the airplane to nose over and automatically unstall.

CONCLUDING REMARKS

Basically the stalling problem consists of the elim-
ination of the rolling instability. Actually the rolling
instability is not only useless but dangerous and should
be avoided, preferably inherently by the design. From
this point of view, the nature of the motion following the
stall becomes unimportant. The complete elimination of
rolling instability, however, does not seem possible. It
may be possible, nevertheless, to delay rolling instabil-
ity to angles of attack that cannot be attained with con-
ventional elevator controls. Another possibility is to
limit the elevator control so that rolling instability
cannot be reached, regardless of the angle at which it oc-
curs. A satisfactory condition might be effected by
either of these suggested methods or by their combination.
Another possibility is to return to the pilot the warnings
to which he is accustomed, or to develop new ones to re-
place them. Stall-approach warnings may include auxiliary
mechanisms that affect the pilot's senses in the same man-
ner as did the older ones; but the most desirable warnings
are those that act directly, eliminating the necessity for
mechanisms and the possibility of mechanical failure.

The present emphasis on stalling characteristics is
primarily a result of the high taper ratios and the low-
wing positions employed on modern airplanes. Compromises
regarding these factors should be considered for each par-

ticular design. High taper ratios are advantageous because they lead to inherently rigid wing structures. The advantages, however, are reduced, if not lost, when the taper necessitates the added weight and complication of tip slots or stall-control flaps.

Similarly, it may be desirable to compromise as to wing position. With small low-wing single-engine airplanes, the undoubted benefits obtained by the simplicity of retracting the landing wheels makes it probable that this low-wing arrangement will be adhered to. With large transport airplanes, the wing height relative to the ground has become so large owing to the increases in propeller diameter that there is no need to keep the fuselage above the wing. Lowering the fuselage relative to the wing would, in addition to improving the elevator-force variation, have no effect on the retracting mechanism for the main wheels and, in the case of the level three-wheel landing gear, would simplify the installation of the front wheel.

Much work remains to be done on the stalling problem. Other possibilities worthy of investigation may be uncovered. All the possibilities heretofore mentioned deserve much more detailed study to obtain a more complete understanding of the mechanism of stall. The subject of limiting the elevator control to permit only angles of attack below maximum lift is still one for debate. Even if limited elevator controls were generally conceded to be acceptable, more knowledge would be required to obtain longitudinal stability such that for all flap and power conditions a single elevator limit would be satisfactory. If sufficient elevator control to exceed the angle of maximum lift is desirable and demanded, then a more thorough inspection of the factors affecting elevator control at high angles of attack is necessary.

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