Journal of Aircraft

VOLUME 3 MARCH-APRIL 1966 NUMBER 2

Effect of Horizontal Stabilizer Vertical Location on the Design of Large Transport Aircraft

A. L. BYRNES,* W. E. HENSLEIGH,† AND L. A. TOLVE‡
Lockheed-Georgia Company, Marietta, Ga.

It is the purpose of this paper to review the aerodynamic, structural, and over-all design considerations, which are affected by horizontal tail location for configurations in which a location high in the vertical fin is not dictated by aft engines, consideration of spray on seaplanes, or other special factors. This review includes the variation of wing downwash, tail dynamic pressure and wing wake effects with tail height, the effect of these factors on selection of horizontal tail area, the static and dynamic tail loads requirements for structural design, and the integrated effect of tail location on airplane performance and stability and control characteristics for specific configurations. Utilization of a high tail location on the C-141 resulted in a reduction in design takeoff weight of 7800 lb below that obtainable with a low tail location. From a stability and control standpoint, the high-tail provides excellent handling characteristics at angles of attack below stall. Above stall, the effectiveness of the high tail is reduced by the wing wake, the severity of this loss being a function of the over-all geometry of the particular configuration. It is concluded that the horizontal tail location is therefore a variable that must be considered along with other design geometry if an optimum over-all design compromise is to be realized.

Introduction

A NUMBER of contemporary aircraft have horizontal stabilizers located on the vertical fin above the fuselage because of the incorporation of engines mounted aft on the fuselage. Recently, there has been some controversy regarding the over-all desirability of such horizontal stabilizer locations. It is the purpose of this paper to review the aerodynamic, structural, and over-all design considerations, which are affected by horizontal tail location, for configurations in which a location high on the vertical fin is not dictated by aft engines, considerations of spray impingement on seaplanes, or other special factors.

Since the C-141 airplane represents a rather recent configuration development study in which this was the case, a review of the design development of this airplane might be useful in quantifying the effect of horizontal tail vertical location on the performance and stability and control characteristics of a specific configuration. Before going into the specific details of the C-141, a review of the basic factors affecting the contribution of the horizontal tail to the longitudinal stability of the airplane is appropriate.

Aerodynamic Considerations

In order to evaluate the effect of horizontal tail location on the longitudinal characteristics of an airplane, it is important that the basic factors affecting the contribution of the horizontal tail to airplane pitching moment be thoroughly understood. The incremental pitching moment coefficient ΔC_{MT} as a function of angle of attack can be expressed as

$$\Delta C_{MT\alpha} = C_{LT\alpha T}(1 - d\epsilon/d\alpha)(l_T/\bar{c})(q_T/q)(S_T/S_W) \quad (1)$$

where

$C_{LT\alpha T}$ = lift curve slope of horizontal tail
$(l_T/\bar{c})(S_T/S_W)$ = horizontal tail volume
q_T/q = dynamic pressure at horizontal tail compared to freestream dynamic pressure

If $d\epsilon/d\alpha$ is less than one, the tail provides a nose-down pitching moment with increasing angle of attack which is a stabilizing influence. If $d\epsilon/d\alpha$ is greater than 1, the tail input is destabilizing. Since, for most aircraft designs, the wing is placed such that the airplane is slightly unstable with the tail off (essentially all of the over-all stability of the airplane is produced by the tail) it is generally necessary that the wing downwash characteristics be such that $d\epsilon/d\alpha$ is less than 1 at all times. The other term of significance, excepting the basic geometry parameters $l_T/\bar{c}$ and S_T/S_W, is q_T/q. The effect of this term on ΔC_{MT} will be discussed in detail later.

Downwash Characteristics of Wings

The downwash behind a wing is primarily a function of the wing planform geometry. Although the downwash characteristics can be modified somewhat by spanwise variations in airfoil section, slats, fences, etc., some general observations can be made on the basis of planform alone. For unswept wings the variation of downwash with angle of attack is generally linear up to stall with some reduction in slope at angles of attack above stall, which increases the stabilizing influence of the horizontal tail.

The downwash characteristics of swept wings are influenced by the interaction between the leading edge vortex, which

Received June 21, 1965; also presented as Preprint 65-331 at the AIAA Second Annual Meeting, San Francisco, Calif., July 26–29, 1965; revision received November 22, 1965.

* Project Aerodynamics Department Manager.

† Engineering Flight Test Pilot.

‡ Dynamics Division Manager.

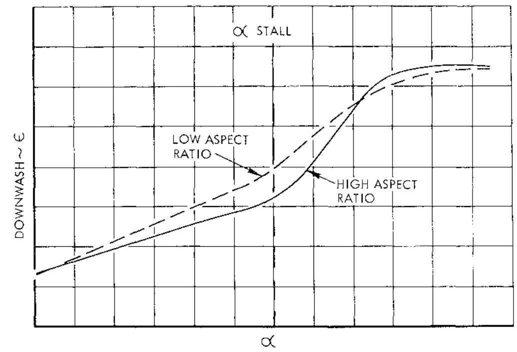

Fig. 1 Swept wing, downwash characteristics.

exists on swept wings, and the tip vortices. At high angles of attack the leading edge vortex tends to "roll up" and pull the tip vortices inboard. This inboard movement increases the downwash behind the center portion of the wing. NASA experiments have shown that this effect is most pronounced on high ($A > 5$) aspect ratio wings.

The downwash patterns behind these wings are generally as shown in Fig. 1. The nonlinearity at high angles of attack is much more pronounced for the high aspect ratio case, although the basic levels of downwash are comparable. This would imply that the pitch-up tendency would be more abrupt on the high aspect ratio configuration.

Another factor produced by sweep is that the wing tips are aft of the basic wing aerodynamic center, and the loss of lift at the tips is destabilizing to the basic wing. Figure 2 summarizes the basic wing pitching moment characteristics of the various planforms. For the straight wings, the reduction in C_M at high α is also accompanied by a reduction in lift. Thus, C_M is more or less constant after the stall. However, on the high aspect ratio swept wings, there is a forward shift of the wing center of pressure associated with the loss in lift near the wing tips, and the value of C_M may actually become positive above stall.

NASA has published the results of a general study to define the combinations of aspect ratio and sweep, which produce unstable wing characteristics at high angles of attack. These data are shown in Fig. 3. The lower boundary is based on wings without modifications to improve the characteristics near maximum lift and therefore is a general boundary of basic planform characteristics. The use of fences, slats, wing twist, spanwise camber variations, etc., can increase appreciably the useable aspect ratio at a given sweep angle. This boundary is also shown in Fig. 3. The C-141 geometry lies

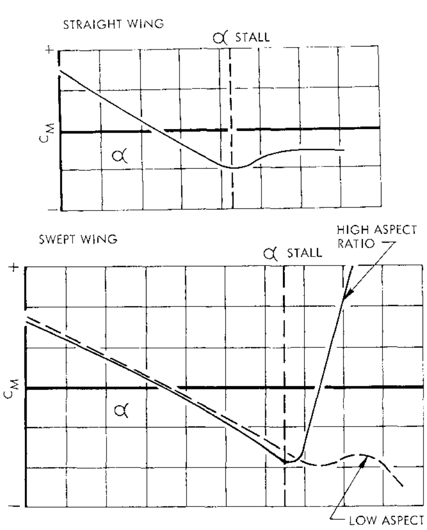

Fig. 2 Pitching moment characteristics, wing only.

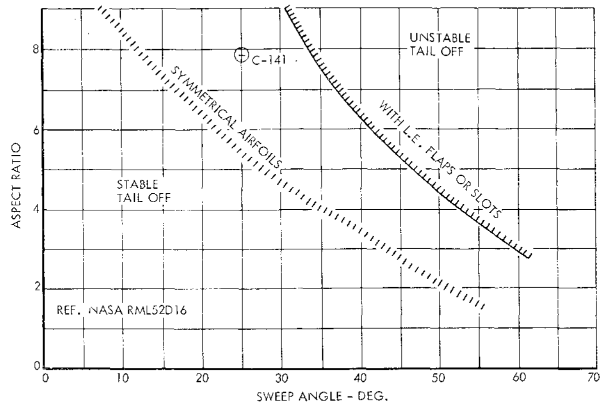

Fig. 3 Effect of sweep back and aspect ratio on wing pitch-up characteristics.

between these boundaries. Although the C-141 does not have slats and/or fences, the wing has been modified substantially by use of camber, twist, and increased leading edge radius on the outboard portion of the wing, to provide stable tailoff stall characteristics. The wind-tunnel test data of Fig. 4 show that the C-141 wing does have a stable break at stall.

Distribution of Downwash and q_T/q

To understand the effect of tail location, some discussion of the flow characteristics behind the wing is in order. Figure 5 presents typical wing wake patterns for low, moderate, and high angles of attack. Typical low and high tail locations also are shown. At low to moderate angles of attack, the low tail is directly in the wing wake and experiences higher values of ϵ and lower values of q_T/q than the high tail. Referring back to Eq. (1), this effect increases the size of the tail required in the low position to provide a given level of stability. Therefore, from this standpoint, the high tail will require less tail area, and hence less tail weight and drag than the low tail. The effect of these considerations on airplane performance will be discussed in detail later.

At high angles of attack (stall and above), this situation is reversed as the wing wake spreads and tends to be displaced upwards. The low tail moves out of the wake, whereas the influence of the wake reduces the effectiveness of the high tail. It can therefore be seen that the high tail enjoys a distinct advantage over the low tail throughout the angle of attack range useable for normal flight maneuvering. At high angles of attack, the low tail moves out of the wing wake and the downwash decreases, making the tail more effective, and hence increasing the stability or nose-down pitching tendency of the airplane.

It should be pointed out that the values of q_T/q shown here are typical of wing effects only, and for this case the value of

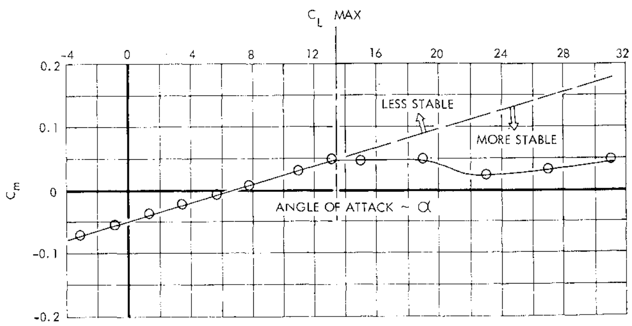

Fig. 4 Variation of pitching moment with angle of attack; horizontal tail off (wind-tunnel data $R_N \approx 2.0 \times 10^6$).

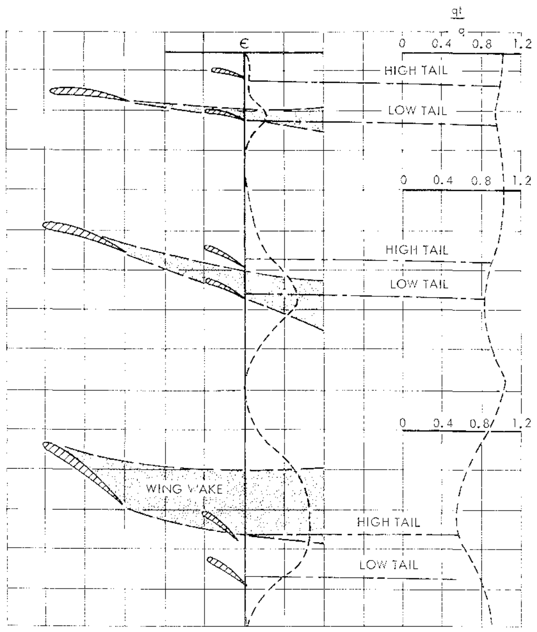

Fig. 5 Typical wing wake patterns.

q_T/q rarely is less than 0.5. If the particular configuration includes some features (for example, aft-mounted engines) which produces an additional wake, the value of q_T/q for a high tail location may approach zero at very high ($\alpha \approx 25°$) angles of attack.

Configuration Characteristics

Now that a basic understanding of the contribution of the various airplane components has been reviewed, some rather specific observations can be made on the effect of tail location as a function of the characteristics of several basic configurations. For convenience, let us establish three basic categories.

Type I: Straight wing airplanes with aspect ratio greater than 5 ($d\epsilon/d\alpha$ constant and somewhat less than 1)

The longitudinal characteristics typical of these configurations are shown in Fig. 6 for tail off, low tail, and high tail. Let us first compare the characteristics (tail on) of the low and high tail locations with both tails having the same tail volume [i.e. $(l_T/\bar{c})\ (S_T/S_W) = K$]. In the normal flight range, the high tail provides greater stability. However, at angles of attack above stall, the low tail provides increased stability and becomes more effective than the high tail. If the tail volume of the low tail is increased to provide the same level of C_M as the high tail, further increases in stability above stall angle of attack are realized.

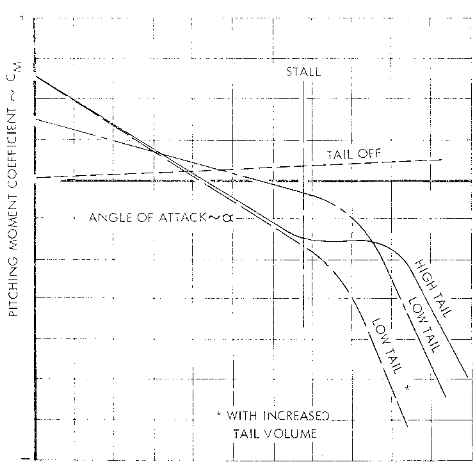

Fig. 6 Type I longitudinal characteristics.

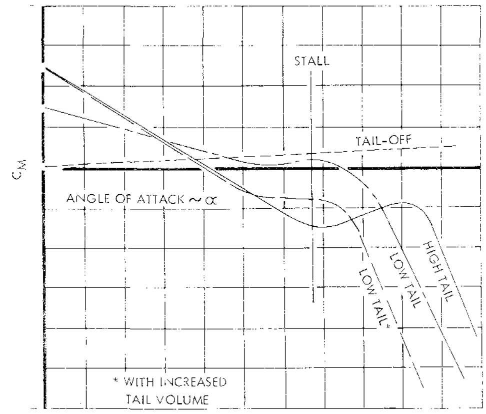

Fig. 7 Type II longitudinal characteristics.

In either case, the stall characteristics would be considered normal and satisfactory since the airplane would always require an increase in control input to increase angle of attack. However, the high tail configuration generally would be able to proceed deeper into the stall area than the low tail arrangement.

Type II: Swept wing airplane with stable break at stall [$d\epsilon/d\alpha$ increases with angle of attack and $(d\epsilon/d\alpha)_{max}$ approaches 1]

Figure 7 presents typical pitching moment characteristics for this type. In this case, the increase in $d\epsilon/d\alpha$ with angle of attack influences the low tail at moderate angles of attack. This characteristic is typical of many swept wing-fighter-type airplanes with relatively low tails and is commonly referred to as "stick force lightening" in accelerated maneuvers. It is most pronounced on airplanes with the tail located above the wing chord plane. The high tail is essentially free of wing downwash characteristics until the stall angle of attack is reached. As the tail enters the wing wake, an area of marginal stability is encountered, causing the airplane angle of attack to increase until a stable gradient is reached. However, this nose-up tendency is mild and controllable, and although not desirable, it does not represent a hazardous or unacceptable condition. Increasing the tail volume for the low tail to provide the same stability produces much the same effect as in the previous case.

Type III: Swept wings with unstable break at stall [$d\epsilon/d\alpha$ increases with angle of attack and $(d\epsilon/d\alpha)_{max}$ is greater than 1]

The characteristics of this type are shown in Fig. 8. For these configurations, the increase in effectiveness experienced by the low tail, as it moves out of the wing downwash, often

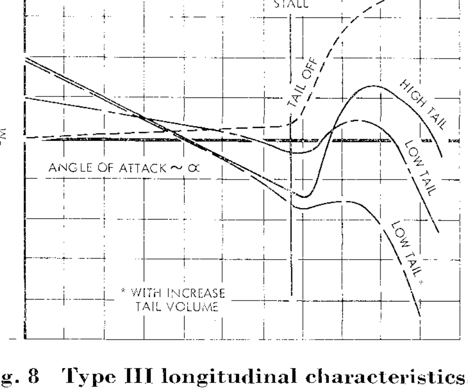

Fig. 8 Type III longitudinal characteristics.

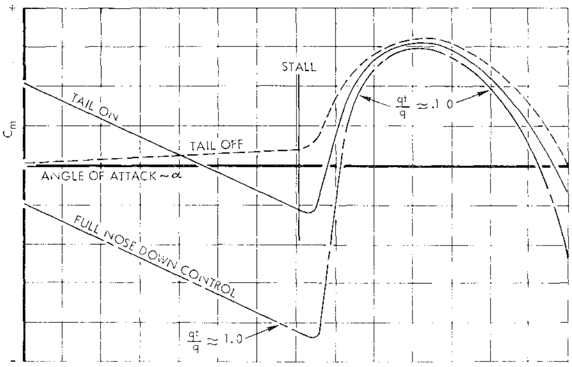

Fig. 9 Effect of reduced qt/q.

can be utilized to eliminate the unstable characteristics of the wing, as shown here for the low tail with increased tail volume. However, with the smaller low tail, a pitch-up tendency still exists. The combination of the high tail with this type of wing will produce a severe, possibly uncontrollable, pitch-up and will, of course, produce unacceptable stalling characteristics. This does not necessarily rule out such configurations since several airplanes with such characteristics have been successfully used by the armed services. However, such airplanes will require the use of a control limiting device to prevent the pilot from entering the area where uncontrollable pitch-up will occur.

It is worth pointing out that combining aft engines with a configuration of this type compounds the problem. As noted earlier, the fuselage-mounted engines produce an additional disruption of the flow and can reduce q_T/q to values as low as 0.1. When this occurs, the control effectiveness is reduced to 10% of the normal flight value and may not be sufficient to bring the airplane back to a controlled flight condition. The characteristics of this configuration are shown in Fig. 9. This figure presents the variation of pitching moment with α for tail off, tail on, and full nose-down control. The airplane is controllable up to stall; however, shortly thereafter, an uncontrollable pitch-up occurs and the airplane continues to pitch up until it reaches a stable trim point at an angle well above stall. At this point, the control power is reduced by the loss of q_T to the point that there is insufficient control to reduce the angle of attack appreciably. If this occurs in flight, the pilot will not be able to regain control of the airplane with normal control action.

It should be noted that the extent to which the aft-mounted engines affect the horizontal tail is a function of the relative size and location of the engines with respect to the tail. All aft engine configurations, of course, do not have the characteristics just described. The effects of engine location on this problem have been thoroughly discussed in Ref. 1.

Figure 10 presents wind-tunnel test data of the C-141 with the tail off, with a T tail (which is the production configuration), and also with a low- or fuselage-mounted tail of the same area as the T tail. Note that the characteristics shown here are typical of the Type I and II configurations discussed previously, as would be expected. It is also obvious that, if a low tail position were used on the C-141, a substantial increase in tail area over that used for the T-tail arrangement would be required to provide the desired stability level for the airplane. The impact of such a change on over-all design optimization will be discussed in detail later.

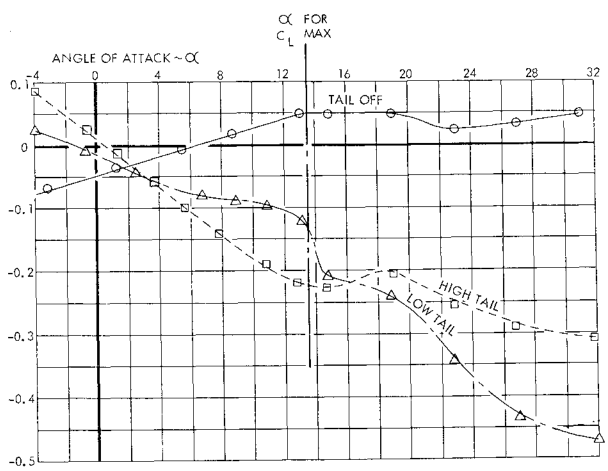

Fig. 10 Variation of pitching moment with angle of attack (wind-tunnel data $R_N \approx 2.0 \times 10^6$).

Structural Considerations

From a static loads standpoint, the design of a T tail is as straight-forward as a fuselage-mounted arrangement. However, because of flutter considerations, it is necessary that the vertical fin and the attachment of the horizontal tail to the vertical be principally designed to stiffness requirements.

There are numerous parameters that must be considered in defining T-tail flutter characteristics. For a practical, efficient, structural-fin design, the effect of the fin torsion to bending frequency ratio of the first modes does not have an appreciable effect on the flutter characteristics, since it generally does not vary over a very wide range. Aerodynamic roll-yaw coupling of the stabilizer-fin does not appear to be appreciable, at least for the designs that have been studied at Lockheed. The effect of higher fin frequency modes is relatively minor because of aerodynamic decoupling. The primary parameter for T-tail flutter is, of course, the fin torsional stiffness, and with this arrangement, the vertical fin stiffness required is heavily dependent on the mass of the horizontal stabilizer. The effect of the stabilizer yaw inertia on flutter speed is shown in Fig. 11. These data are in agreement with the results obtained from flutter model data of more than fifty various T-tail configurations as tested by NASA, Wright Air Development Center (WADC), Lockheed, and others.

Because of this characteristic, it is very important to design for minimum horizontal tail size in order to minimize the fin stiffness requirement. A comparison of the vertical fin stiffness requirement between a low tail and a T-tail design is shown in Fig. 12. These data show that the T tail requires about $1\frac{1}{2}$ times the stiffness at the vertical fin root and about 40 times the stiffness at the tip than does the low tail arrangement. Obviously, this results in a higher structural weight for the vertical fin for the T tail.

Another important parameter for a T-tail design is the effect of stabilizer dihedral on the flutter speed, which directly affects the required fin stiffness. Figure 13 illustrates that the flutter speed can be increased appreciably by incorporating negative dihedral into the stabilizer design. For

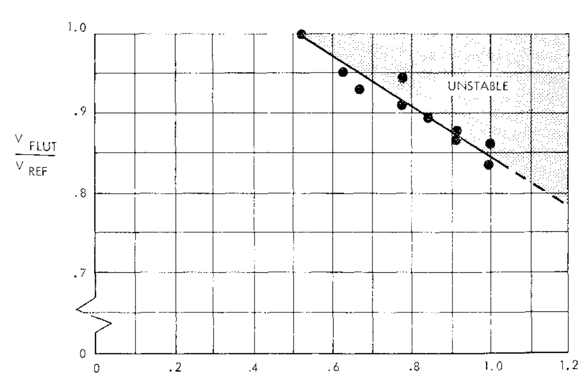

Fig. 11 Effect of stabilizer mass on T-tail flutter speed (measured model data).

instance, 5° of stabilizer negative dihedral can result in a reduction of approximately 31% in the required fin stiffness for flutter reduction. Although this feature was not incorporated in the C-141, it is certainly worthy of consideration in future designs.

The flutter design of the T-tail stabilizer-elevator is similar to that for a low tail configuration and presents no different complications. In order for a low-tail rudder to be flutter free, it must be designed to be balanced, either adequately statically and dynamically, or it must be effectively irreversible from a flutter standpoint. Mass balancing requires the addition of a large amount of weight to the rudder leading edge. As a result, the strength of the rudder structure must be increased to carry the higher loads with an additional increase in weight which necessitates more balance weight, etc. Irreversibility generally requires that multiple actuators be located along the rudder span. This dictates that the backup structure of the fin and rudder be beefed-up in order to provide high stiffnesses for obtaining the required rudder frequencies. The rudder's lowest frequency should be at least 1.5 times the highest fin frequency with which it could couple in a flutter mode. Since the fin frequencies for a low tail are relatively quite high, it is extremely difficult to attain an effectively irreversible rudder on a large aircraft without a considerable weight penalty.

With a T tail, the vertical fin bending and torsional frequencies are reduced markedly by the mass of the horizontal stabilizer. In flight, the rudder frequency for an unbalanced, rotationally free surface is a function of the aerodynamic hinge-moment or spring, which, in conjunction with the mass of the rudder, will result in a rudder frequency that increases with dynamic pressure. If the rudder mass is sufficiently low, this frequency will be higher than the critical fin frequencies and flutter cannot develop. Any additional restraint produced by the rudder control system will be beneficial in further increasing the rudder frequency. The T-tail design, therefore, allows a flutter-free rudder to be built which does not require any balance weights and it does not have to be effectively irreversible. This obviously results in a minimum weight rudder that has to be designed only for airloads and sonic fatigue requirements. This also reduces the weight required in the fin for rudder attachment.

As an illustration, the rudder for the C-141A T tail, which does not incorporate any balance weights, weighs 216 lb. The same size rudder for a low-tail configuration would have a weight of approximately 846 lb, a difference of 630 lb.

Comparison of Structural Weights

As previously discussed, the T-tail and low-tail configurations each have various advantages and disadvantages from a weight standpoint. Each configuration must be designed to be satisfactory from an aerodynamic standpoint and from the structural standpoints of loads, flutter, sonic fatigue, and weight. The structural weight is a very important consideration since airplane performance directly depends upon this parameter. A comparison is given for the structural weights of the C-141A T tail and a low tail that would give equivalent stability and control characteristics and meet the same structural design and drag critical Mach number requirements. A value of 478 lb has been reported previously as the structural weight savings of the T tail, as compared to the low tail for the C-141A airplane. This weight value was originally established early in the design stages of the airplane and does not include a number of weight advantages which became apparent as the design progressed. For instance, it does not include the large weight advantage of not requiring balance weights on the rudder. It appears that this value of 478 lb is actually about 1308 lb. A summary of actual weights for the C-141A T tail, and estimated values for a low tail are shown in Table 1.

Table 1 Actual weights for C-141 T tail and estimated values for low tail

Item	T tail, lb	Low tail, lb
Elevator	777	1676
Stabilizer	2268	3342
Rudder	216	846
Fin	2755	1860
Bullet	400	None
Total	6416	7724

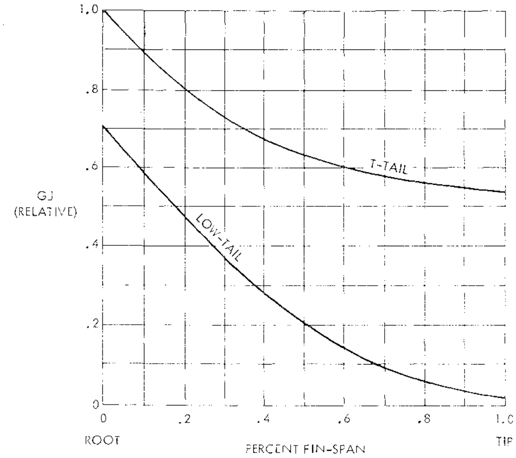

Fig. 12 Comparison of fin torsional stiffnesses for low-tail and T-tail designs.

The weight advantage of the T tail is primarily due to the elimination of rudder balance weights and the lower weight associated with the smaller stabilizer-elevator. Of course, the major weight disadvantage is the heavier fin.

The structural weight advantage of the T tail becomes more evident as the size of the aircraft increases. Advantage may be taken of the stabilizer negative dihedral effect on stiffness to optimize the fin design so that stiffness and loads requirements more nearly agree with each other, thus resulting in a reduced fin weight.

Horizontal Tail Loads

Flight tests have been conducted on an extensively instrumented C-141A aircraft to measure empennage loads resulting from penetration into high angle-of-attack stall conditions. During stalls beyond maximum wing lift, large oscillating inertia loads, which are due to a structural response of the tail to the disturbed flow in the wing wake, are encountered. With the flaps up, the symmetric bending mode of the horizontal stabilizer is predominate at a frequency of 7.0 cps. With the flaps down, a 4.0-cps antisymmetric excitation of

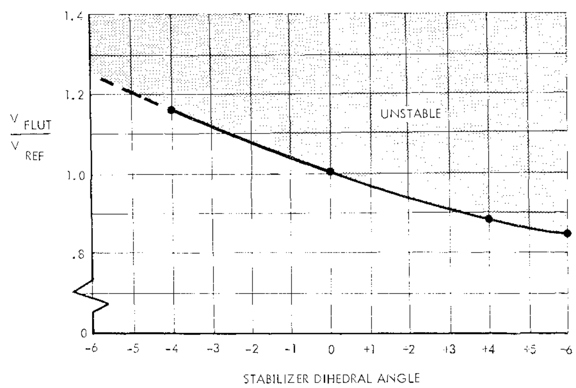

Fig. 13 Effect of stabilizer dihedral on T-tail flutter speed (measured model data).

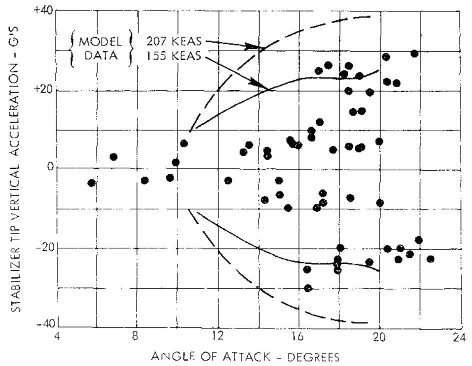

Fig. 14 Comparison of T-tail stall buffet response measured on airplane and flutter model (airplane data ~ 180 KEAS).

the entire empennage is encountered, producing combined bending-torsion load on the vertical fin. Since the dynamic loads on the horizontal stabilizer in the flaps-down configuration are considerably lower than in the clean configuration, the following discussion will be limited to the clean configuration.

The results of the flight tests indicated that the stabilizer loads increase rather rapidly with increased angle of attack and/or dynamic pressure. An experimental wind-tunnel model investigation was therefore conducted simultaneously with later flight tests in order to permit a rapid and systematic study of the stabilizer buffet loads at angles of attack above stall. These model tests were conducted in a low-speed wind tunnel on a $\frac{1}{24}$th scale flutter model of the C-141A airplane. The model was instrumented to measure tip accelerations of the stabilizer and bending moments at four spanwise stations along the stabilizer. The test procedure was to hold the wind-tunnel speed and model angle of attack constant for approximately 20 sec, while time histories of loads and accelerations were recorded on magnetic tape and direct writing records. The angle of attack was varied from $-6°$ to $+20°$ for a range of wind-tunnel speeds.

The results of the model tests are compared with data obtained from the C-141A stall flight test program. Figure 14 shows a comparison of the tip accelerations of the horizontal stabilizer with angle of attack. The data points represent peak accelerations measured during a number of airplane stall tests at approximately 15,000 ft and at speeds of 180 KEAS. Data for the 15,000-ft-altitude tests were analyzed for comparison with the model data since the model was dynamically scaled to simulate 15,000 ft. Superimposed on these flight test data points are the envelopes of peak acceleration measured on the model at scaled airplane speeds of 155 and 207 KEAS.

The accelerations measured on the model are in good agreement with those obtained on the airplane. The model data indicate that stall is reached at angles of attack somewhat lower than that of the airplane because the airplane is operating at a Reynolds number of approximately 30,000,000, whereas the model's Reynolds number is about 300,000. Consequently, the model reaches $C_{L_{max}}$ at lower angles of attack. Estimates based on C-141A aerodynamic data predict this difference to be of the order of 4° to 6°, which is in agreement with the data shown in Fig. 14.

Figure 15 compares the stabilizer incremental dynamic bending moments with angle of attack for T-tail and low-tail configurations at equivalent airplane speeds of 133, 187, and 286 KEAS. These test results do not include the effect of Mach number since the data were obtained at low wind-tunnel speeds. Figure 15a shows that the buffet induced dynamic loads for the low tail are higher than those for the T tail at angles of attack up to approximately 14°, which corresponds roughly to the angle of attack for stall at low Mach numbers. Above this angle the T-tail loads become greater. At the higher Mach numbers, which are typical of accelerated maneuvers, the stall angle of attack is reduced and the dynamic loads on the low tail are greater than those of the T-tail, as shown in Figs. 15a and 15b. The angles of attack discussed here are referenced to the fuselage reference line (FRL). The C-141 wing has an incidence of 5° with respect to the FRL.

The higher dynamic bending moments occur on the low tail because the stabilizer is initially immersed in the wing wake. Until the angle is reached at which the low tail emerges from the wake, it is affected more by the greater wake turbulence than is the T tail. Initially, the T tail is well above the wing wake and becomes immersed in the wake only at high angles of attack. Thus, in accelerated flight at high speed, the T tail remains outside the wake since the maximum angle of attack is limited by airplane limit design strength. For these cases, the dynamic loads on the low tail will be considerably higher than for the T tail. Conversely, at low speeds in unaccelerated stalls where high angles of attack (considerably above maximum lift) can be obtained, the T-tail dynamic loads are higher.

Performance Considerations

The use of a high rather than a low or cruciform tail provides the following areas of improvement.

1) When the high tail is used on a swept-back vertical stabilizer, the tail-arm available is automatically increased; this allows the use of a smaller horizontal stabilizer for equal tail volume and thus reduces the weight and skin friction drag of the horizontal surface.

2) The rate of change of downwash with angle of attack decreases as the distance of the horizontal tail above or below the wing wake is increased. Thus a high tail operates in a region of reduced downwash. This permits the use of a lower tail-volume coefficient, i.e., a reduction in horizontal tail area, for a given wing configuration. Thus, there is an appreciable reduction in tail weight and drag.

The preceding factors, in the case of the C-141A, permitted reductions in horizontal tail area. This reduction in area of 32%, coupled with the cleaner installation, resulted in a drag reduction of $C_D = 0.0006$ or 2.5% of cruise drag. It should be noted that this is the effect of the tail modification alone, with the rest of the airplane geometry remaining fixed.

On a fuel-limited mission, such as the 5500-naut-mile range mission, the drag improvement is equivalent to an increase in payload of 6000 lb. Together with the previously noted

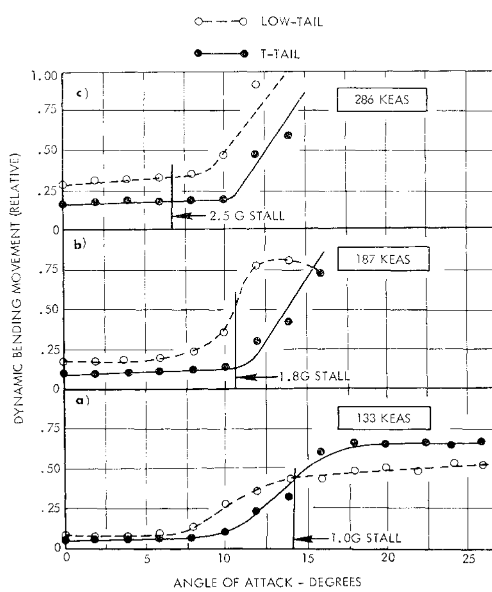

Fig. 15 Comparison of T-tail and low-tail stabilizer dynamic bending moments at stall buffet (flutter model test data at 20,000 ft).

weight saving of 1300 lb, this is a total increase in payload at 5500 naut miles of 7300 lb. In the takeoff weight-limited case, such as the 4000-naut-mile mission, the drag reduction produces a payload increase of 2600 lb which produces an equivalent structural weight decrease of 3900 lb. During the proposal state of the C-141, the growth factor (net increase in airplane takeoff weight per pound of structural weight) was about 2.0, and so the use of the T tail reduced the maximum design takeoff weight by about 7800 lb. It is obvious, therefore, that in the area of performance, the high tail location provides both a reduction in over-all airplane weight and drag, which are particularly significant in the case of large transport category aircraft.

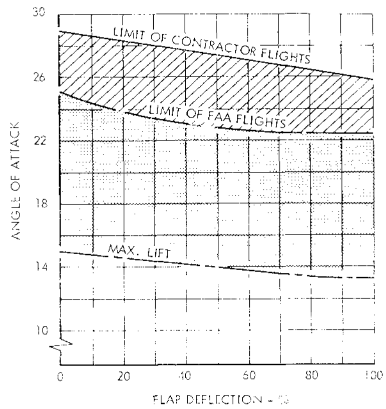

Fig. 16 C-141 summary of maximum angles of attack experienced during stall test.

Airplane Handling Characteristics

Thus far, we have discussed the relative merits of the horizontal tail vertical location from a technical analysis standpoint only. But what are the practical considerations involved from a pilot's point of view?

Depending to a large extent on the thoroughness of design of the entire airplane, it is possible for the horizontal tail vertical location to have very little effect on the pilot's impression of flight characteristics of a large transport airplane. This is especially true in the normal mission operating envelopes of speed, altitude, and maneuvering flight. Another very influential factor, in the pilot's evaluation, is the design of the flight control system. The use of a properly tailored fully powered control system provides the designer with the capability of substantially improving undesirable characteristics of a given configuration. The C-141 airplane has fully powered irreversible control systems. There is no feedback of control surface hinge moments to the pilot.

Longitudinal control forces are provided by a bobweight-feel-spring system. The feel spring is modulated with dynamic pressure to provide increased maneuvering force gradients and stick force stability for high-speed flight. A Mach trim compensator is provided to eliminate the characteristic "tuck" at transonic speeds and a yaw damper is incorporated to augment the damping of lateral-directional damping.

The control forces are relatively light for an airplane of this size, providing the pilot with the feeling of a highly maneuverable machine with good basic stability characteristics throughout the normal flight range of the airplane.

Stall Characteristics

The characteristics of the stalls, as have been shown in previous design discussion, are influenced terminally by the over-all design of the entire airplane. Because of the destabilizing effect of the T tail as it enters the wing wake at or near stall, an uncomfortable or completely destabilizing pitch-up can occur on some configurations. By all means, a design should never be such that the pitch-up results in a locked up condition from which normal recovery can not be made. Nor, when entering the stall at a closure rate as high as 4 knots/sec should the pitch-up produce what is considered a deep stall. A deep stall is defined as a condition well above the angle of attack for maximum lift, where some airplanes have exhibited prolonged periods of uncontrolled flight.

In initial stall tests, lateral control was critical at angles of attack between 16°–20°, flaps up. The rather abrupt separation of the wing between the engine pods produced sharp roll accelerations. These lateral disturbances, coupled with the nose-up trim change at stall, were considered very uncomfortable by the test pilots, and it was considered that some improvement in lateral controllability was mandatory if penetrations into stalls at angles of attack greater than about 20° were to be pursued.

The lateral controllability was improved by installing vortex generators between the engines at the 25% chord of the wing to delay the growth of the initial separation in this area. Also, a small stall strip was located on the inboard wing leading edge to incite earlier separation of the center section and thereby improve the longitudinal characteristics. With these changes incorporated, penetrations into α's above 20° were continued.

During an entry into the stall at 1 knot/sec in clean configuration, if the elevator was held fixed at first indication of stall, (approximately 16°) the angle of attack would increase to 20°. From this point on, an increase in α required an increase in an elevator up to the maximum angle of attack tested (29°). At this slow entry rate, this was the maximum angle of attack that could be attained flaps up using full up elevator trimmed at 1.4 V stall at full forward center of gravity; but at the aft center-of-gravity limit, this same angle of attack could be reached with a little less than half the elevator travel available under the same conditions of trim. It is obvious that slower trim speeds and/or faster entry rates would result in even greater capabilities of the elevator to produce excessively high angles of attack. It should be noted that the airplane was controllable at least to the point of maintaining wings level at these angles of attack flaps up. Buffet intensity at these conditions was severe, and dynamic tail loads measurements indicated design values were being obtained locally in the outer 60% of the tail span.

With the flaps down, the longitudinal characteristics were essentially the same except, of course, stall occurred at lower angles of attack (α = 13° to 14°) and the maximum attainable angles of attack were reduced to about 20° to 22° at the forward center of gravity; at the aft center-of-gravity maximum angles investigated were limited to 24° to 26° because lateral control became ineffective at an angle of attack of about 26°, and at higher angles of attack the airplane was uncontrollable laterally. Longitudinal and directional control remained effective in all areas investigated.

As a result of these tests, it is considered that the airplane exhibits satisfactory controllability in the stall and deep stall region at angles of attack 10° to 13° beyond maximum lift. It is noted that these angles were obtained without use of full control inputs at the aft center-of-gravity conditions. No attempt was made to determine the maximum possible angle of attack attainable with full control. Because of the obvious compromises to safety inherent in repeated testing of this type, the contractor and evaluating agencies agreed to a nominal angle of attack limit of 20° for demonstration purposes.

Figure 16 summarizes the angles of attack at various flap deflections covered during the contractor stall tests and the Federal Aviation Agency (FAA) and Air Force evaluations. Note that a second series of tests actually exceeded the nominal 20° limit by as much as 6° in some configurations. The angles of attack corresponding to maximum lift are also shown on this figure.

It is interesting to note that the FAA evaluation of the airplane at this time was that, although the attitudes were extreme and the airplane buffet level moderate to severe, the

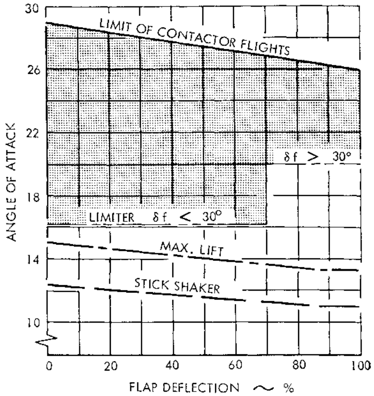

Fig. 17 C-141 maximum angles of attack with angle of attack limiter.

airplane was controllable about all axes at these angles of attack to a degree that might lead a pilot to conclude that the airplane was not completely stalled. In order to obtain FAA certification within the forementioned limitation, it was required that a positive angle of attack limiting device be incorporated in the airplane.

Figure 17 presents the maximum angles of attack attainable with the angle-of-attack limiter installed as compared with the maximum angles attained during the stall programs. Note that the limit angles are, in all cases, above the angle of attack for maximum lift. A stick shaker is also included in the system to provide positive stall warning prior to attaining maximum lift.

In summary, it is true that careless application of a high T tail could drastically affect some of the flying characteristics of an airplane. But if the subject airplane were given to an experienced engineering test pilot without knowledge of the tail configuration, it is the writers' opinion that he would be hard pressed to determine, without any doubt, what vertical location of the horizontal tail he was testing.

With regard to stall demonstration of large transport aircraft, there is considerable concern within the industry as to whether these aircraft should be required to perform the same stall characteristics tests as required of the relatively small airplanes of a generation ago. From a standpoint of dollar risks involved alone, the requirement of placing a $10,000,000 300,000-lb aircraft in an uncontrolled attitude in order to assure that controlled flight can again be attained is somewhat incongruous. When this is coupled with the inherently slower response of the large airplane which increases the time and altitude loss required to regain level flight if a severe upset should occur, and the possibility of encountering loads induced by structural and airplane dynamics, which exceed the structural design criteria for the airplane, the exposure becomes staggering. A more logical and certainly more practical approach of limiting the pilot's control capability to prevent the airplane from entering such areas would certainly be more prudent. It is gratifying to see this approach being taken on the more advanced large transport airplanes pending certification at the present time.

Conclusions

From the preceding discussion, it can be concluded that the high tail location enjoys some significant advantages from a performance and stability and control standpoint in the normal useable flight range (angles of attack up to stall) of the airplane. At angles of attack above stall, the effectiveness of the high tail is reduced by the wing wake. The severity of this loss in effectiveness is a function of the geometry of the particular configuration. For swept wing ($\lambda > 30°$) configurations with aspect ratios above about 6, and particularly in combination with aft-fuselage-mounted engines, the loss in severe and for some configurations has resulted in complete loss of longitudinal control at extreme angles of attack. For straight, or moderately ($\lambda < 30°$) swept wings, the loss is small and the stall characteristics would generally be satisfactory. In either case the high tail configuration generally will be able to proceed further into the stall than the low tail.

The relative importance of performance and stall characteristics must be weighed against the required mission roles of the configuration in question. Obviously, in the case of a primary trainer, highly maneuverable fighter, or carrier-suitable aircraft, stall characteristics would be of major concern. For transport aircraft, the possibility of encountering an extreme stalled condition in normal use is extremely remote; the stall characteristics, therefore, are of less significance, providing that the minimum useable speeds are not unduly compromised.

It is obvious that horizontal tail location is therefore a design variable that must be considered along with other design variables in arriving at the final design compromise. It should be emphasized that, with any configuration, it is prudent to obtain wind-tunnel test data well beyond the speed and angle-of-attack ranges anticipated to be obtained in flight. In the case of configurations with high horizontal tail locations, it is particularly important to obtain such data at angles of attack well beyond stall angles of attack, and that detailed analyses of the airplane characteristics based on these data be carried out to insure that no unacceptable control problems will be encountered in this area.

Reference

[1] Taylor, R. T. and Ray, E. J., "Deep stall aerodynamic characteristics of T-tail aircraft," NASA Conference on Aircraft Operating Problems (May 1965).