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# RESEARCH MEMORANDUM

STUDY OF THE CANARD CONFIGURATION WITH PARTICULAR  
REFERENCE TO TRANSONIC FLIGHT CHARACTERISTICS  
AND LOW-SPEED CHARACTERISTICS AT HIGH LIFT

By Charles W. Mathews

Langley Aeronautical Laboratory  
Langley Air Force Base, Va.

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## NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

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## SUMMARY

Results are presented of a brief study of the flight characteristics of the canard configuration at transonic and supersonic speeds. Known problems concerning the low-speed characteristics of the canard are also investigated.

Previous experimental results of free-fall tests have shown that for a sweptback wing in combination with a body of high fineness ratio, reduction in the interference drag can be obtained at transonic and low supersonic speeds by locating the wing aft of the body maximum diameter.\* The present study indicates that such a relative location of wing and body is better suited to the canard arrangement than to the tail-aft arrangement, although the effect on over-all drag of a forward horizontal tail is not known. Forward location of the horizontal tail also avoids stability and trim changes at high Mach numbers due to the proximity of the tail to the wing wake, but similar changes will occur at the wing of a canard due to the tail wake. The results of this study are thought to indicate that wake effects might be less serious for the canard arrangement, although few experimental data are available to confirm this opinion. Stability and trim changes due to wake effects can be eliminated with a tailless airplane, but experimental data show that the large shifts in wing aerodynamic center which occur at transonic and supersonic speeds produce large changes in stability and trim of tailless configurations. This study shows that the effect of aerodynamic-center shift on the stability and trim of a canard airplane should be relatively small.

Past experience with canard aircraft indicates that satisfactory stalling characteristics are difficult to obtain. A study made by J. Foa shows that satisfactory stalling characteristics may probably be obtained by placing the allowable center-of-gravity range far enough forward so that the horizontal tail stalls prior to the wing. Although this limitation on the center-of-gravity range reduces the maximum lift of the wing,

a simplified analysis indicates that the large lift increment produced by the horizontal tail should roughly compensate for this reduction. The spanwise variation of tail wash over the wing may further reduce the maximum lift obtainable, and this effect was not included in the aforementioned analysis. Advantageous use of high-lift devices on a canard airplane can be attained only if the pitching moment due to flap deflection can be compensated by use of flaps on the horizontal tail or by auxiliary lifting surfaces. The analyses of high-lift characteristics indicate that if swept wings are used, maximum lift coefficients comparable to an airplane with a conventional tail location can be obtained for a canard airplane over a reasonable center-of-gravity range.

## INTRODUCTION

Many serious problems are created by the occurrence of marked changes in the flow about an airplane as the speed of sound is approached and exceeded. Considerable research effort has been placed upon both theoretical and experimental investigations to determine means for solution of these problems, in particular the reduction of drag and the provision of satisfactory stability and control characteristics. Results of these investigations indicate that, in order to obtain practical transonic and supersonic flight of man-carrying aircraft, some departures from the conventional airplane configuration may be warranted.

One type of configuration which has been given some consideration for use as a missile is the canard arrangement. In order to evaluate the possibilities of the canard as an airplane, a study has been made of its high-speed-flight characteristics. At the same time, some of the known problems connected with the low-speed characteristics of the canard were investigated. Results of this study are presented herein. A three-view drawing of a configuration which embodies the features discussed is presented in figure 1.

## HIGH-SPEED CHARACTERISTICS OF CANARD AIRPLANE

### AS COMPARED TO OTHER AIRPLANE TYPES

On approaching the speed of sound an airplane may exhibit a number of unsatisfactory characteristics. First, large increases in drag occur which preclude efficient operation and, with existing power plants, seriously limit the range of the aircraft; second, unsteady flows may occur about the airplane, even in level flight, which may cause structural damage; and, third, large and/or abrupt changes in trim and stability may take place. In some cases adequate control may be maintained throughout

these stability and trim changes, particularly if the changes occur slowly and if the associated stick-force variations are small. Changes in stability and control, however, are always unsatisfactory from a handling-qualities standpoint and at high speeds may be very dangerous.

Reduction of drag. - Both theoretical and experimental investigations have indicated means for appreciably reducing the drag of airplane components at transonic and supersonic speeds, that is, the use of bodies of high fineness ratio and the use of wings swept well behind the Mach cone. If sweptback wings are used, a problem exists concerning a practical arrangement of the components of an airplane. For the tail-aft arrangement, the wing-fuselage juncture must be located relatively far forward on the body if a reasonable tail length is to be provided. Although the relative position of the wing and fuselage of an airplane is usually not important from the standpoint of drag at low speeds, tests of two free-fall models reported in reference 1 indicate that at transonic speeds the total drag of a wing-body combination varies appreciably with the relative location of the wing and body. These results, which are presented in part in figure 2, show that the total drag of the tested combination was lowest when the wing root was located in a position aft of the body maximum diameter, that this drag difference resulted chiefly from a difference in body drag, and that the body drag with the wing in the aft position was appreciably less than the drag of the body without wings.

Consideration of the geometry of an airplane having a sweptback wing located behind the body maximum diameter indicates that such an arrangement is not well adapted to a rearward location of the horizontal tail, not only from the standpoint of providing adequate tail length but from the standpoint of balance. The center of gravity of such an airplane would have to be well behind the body midpoint in order to provide a reasonable variation of pitching moment with angle of attack. Because of this requirement, a light forward section of the fuselage would be necessary and much of the fuselage volume could not be used for payload and fuel.

Geometrically, the wing-aft arrangement is well suited to use as a canard-type airplane. The stability requirements alone dictate that the center of gravity must be a reasonable distance ahead of the aerodynamic center of the wing-body combination. This requirement places the center of gravity near the body midpoint and insures a large tail length. The effect of a forward location of the horizontal tail on the fuselage and wing drags is not known.

Reduction of buffeting. - Another high Mach number problem associated with a rearward location of the horizontal tail is the occurrence at transonic speeds of severe buffeting of the airplane or its controls which results from the unsteady-flow conditions at the horizontal tail caused by flow fluctuations due to the wing wake. In several designs

for high-speed airplanes the horizontal tail has been located high on the vertical tail for this reason. This type of tail location not only presents structural difficulties but may not eliminate buffeting in accelerated maneuvers where the tail may move into the region of flow fluctuations. With the horizontal tail located ahead of the wing the effect of the wing wake on the horizontal tail is eliminated, but effects of the tail wake are present at the wing root. It is thought that the buffeting should be less serious under these conditions, however, because only the wing root would be affected, and the tail should produce a smaller disturbance than the wing. No experimental data are available, however, to confirm this opinion. The wing is also a better structural member than the horizontal tail for the absorption of buffeting loads, and the shaking of the longitudinal control caused by the flow fluctuations due to the wing wake would be eliminated.

Longitudinal stability and control.- The chief causes for the changes in longitudinal trim and stability near and above the speed of sound may be itemized as follows:

- (1) Changes in the variation of lift coefficient with angle of attack of the lifting surfaces
- (2) Change in angle of zero lift of the lifting surfaces
- (3) Shifts in aerodynamic center of the wing
- (4) Variations in the dynamic pressure at the tail
- (5) Variations in downwash at the tail
- (6) Loss or reversal of elevator lift effectiveness

The first two changes listed above may be minimized through proper selection of airfoil plan forms and sections, such as thin symmetrical sections with plan forms swept well behind the Mach cone. Item 3, the shift of the wing aerodynamic center, is important when considering the possibilities of a tailless configuration for transonic and supersonic flight. Such a configuration has a definite advantage over the tail-aft arrangement in that trim and stability changes at the tail are eliminated completely; but because a very small static margin is essential toward providing adequate control, use of wings with large aerodynamic-center shifts is precluded. Most wings will have large aerodynamic-center shifts through the transonic speed range. As an example, results of tests by the wing-flow method of a 35° sweptback airfoil-flap combination (reference 2) show that a 17-percent rearward shift in aerodynamic center occurred between Mach numbers of 0.85 and 1.10. An aerodynamic-center shift of the same magnitude was obtained from other wing-flow tests of a semispan model of a tailless airplane. Since flaps

are generally used as a longitudinal control for tailless airplanes, additional adverse effects on longitudinal control characteristics may be expected from the losses in flap effectiveness which occur at transonic speeds.

The effects of aerodynamic-center shift and loss in flap effectiveness on the longitudinal stability of a tailless configuration have been computed from the results of reference 2. In this case the major changes in stability result from the aerodynamic-center shift. The configuration assumed in this computation consists of a  $35^\circ$  sweptback wing of constant chord and aspect ratio 3.04 with a 25-percent-chord full-span flap. The results of this calculation are presented in figure 3 where the variation of flap deflection with trim lift coefficient

$\frac{d\delta_c}{dC_{Ltrim}}$  is plotted as a function of Mach number. The parameter  $\frac{d\delta_c}{dC_{Ltrim}}$  is an indication of the airplane's longitudinal stability and should be nearly constant at low subsonic speeds. The center-of-gravity position of the tailless configuration was selected so that the value of  $\frac{d\delta_c}{dC_{Ltrim}}$  was 0.1 radian at a Mach number of 0.55, which represents a reasonable value of stability. As shown in figure 3 the value of  $\frac{d\delta_c}{dC_{Ltrim}}$  for the tailless airplane increases rapidly and in a somewhat irregular manner to about seven and one-half times the low-speed value at a Mach number of 1.1. This increase means that at a Mach number of 1.1, seven and one-half times more control deflection would be required to produce a given change in lift coefficient than would be required at a Mach number of 0.55.

Results of a corresponding calculation are shown in figure 3 for a canard configuration. The same wing was assumed as for the tailless airplane; but an all-movable tail, geometrically similar to the wing and having the same area as the flap of the tailless airplane was placed  $3\frac{1}{2}$  chord lengths ahead of the wing. The effect of tail wash on the wing is neglected in this calculation and neglect of this effect may make the calculation slightly optimistic. Again the center-of-gravity position was chosen to make the value of  $\frac{d\delta_c}{dC_{Ltrim}}$  0.1 at a Mach number of 0.55.

For the canard, the plot of  $\frac{d\delta_c}{dC_{Ltrim}}$  against Mach number has a slow

increase to one and one-half times the low-speed value at a Mach number of 1.1. This result indicates that the control characteristics of the canard are only slightly affected by the aerodynamic-center shift of the wing.

Unpublished data from the Ames Aeronautical Laboratory present another means for reducing the adverse effect of wing aerodynamic-center shift. This arrangement, which combines some of the characteristics of the canard and the tailless airplane, incorporates a forward-located trimmer surface that is allowed to float with the wind at subsonic speeds and is locked rigidly at supersonic speeds. The trimmer does not affect the longitudinal stability of the aircraft while free to float, but produces a forward shift in neutral point on being locked. This arrangement can be designed so that the forward shift in neutral point compensates the rearward shift due to change in wing aerodynamic-center location. This trimmer arrangement shows promise for aircraft having a small center-of-gravity range. With the trimmer locked, the configuration has the characteristics of a tailless airplane and, therefore, large center-of-gravity movements during flight cannot be tolerated. It is also important to note that locking the trimmer prior to the aerodynamic-center shift would, in general, produce longitudinal instability. Thus, considerable discretion on the part of the pilot would be required in use of the device. The foregoing consideration indicates further that the trimmer must float in the transonic speed range. Because of the possibility of unsteady flows at transonic speeds, the trend has been toward irreversible flight controls for high-speed aircraft. In the transonic range the floating trimmer would not improve the control characteristics of this arrangement over that for a tailless airplane, but locking the trimmer should appreciably increase maneuverability at supersonic speeds.

The largest trim and stability changes that occur for an airplane with a rearward tail location are usually caused by changes in the flow at the horizontal tail or by changes in the aerodynamic characteristics of the horizontal tail. Large variations in wing downwash characteristics may occur in the transonic speed range due to changes in the load distribution on the wing and other changes in its lift characteristics. Supersonic theory indicates that for unswept wings large changes in the downwash variation with angle of attack  $d\epsilon/d\alpha$  occur with changes in Mach number. (See reference 3.) Experimental evidence confirms this result and also shows that  $d\epsilon/d\alpha$  will be appreciably affected by variations in lift coefficient at a given supersonic Mach number. (See reference 4.) A typical theoretical variation of the downwash parameter  $d\epsilon/d\alpha$  in the region of the horizontal tail of a conventional airplane with unswept wings is shown as a function of Mach number in figure 4. The theoretical variation of  $d\epsilon/d\alpha$  shown for the supersonic range does not account for the effect of variations in lift coefficient. Since supersonic downwash theory for swept wings is very complicated,

computations have not been made for this case, and few experimental data are available. It is believed that similar variations of  $de/d\alpha$  with Mach number might be expected for a sweptback wing since an Ackeret type flow exists in the vicinity of the wing root.

A possible means for reducing downwash and other wake effects, as in the case of buffeting, is to place the horizontal tail forward of the wing. Again the effects which produce the undesirable changes are removed from the tail; and although these effects are then present at the wing root, it appears that they should be smaller because only a small portion of the wing area would be affected. The effect of tail downwash on the wing would be further reduced because of the counter-acting presence of the upwash from the tail over the portion of the wing outboard of the tail tips.

The functions of the horizontal tail differ, depending on whether the canard or the rearward tail location is considered. The horizontal tail of the canard serves only to regulate the trim of the aircraft, and the tail actually produces an unstable variation of pitching moment with angle of attack. A necessarily large stable pitching-moment variation is supplied by the wing. In the case of the tail-aft airplane, the horizontal tail not only regulates the trim but must also supply a large stable variation of pitching moment, and the aerodynamic characteristics of the horizontal tail are chiefly governed by stability requirements.

Consideration of the unstable pitching-moment variation produced by the tail of the canard indicates the desirability for keeping this variation small while keeping the maximum increment in pitching moment produced by the tail large. In this manner a more rearward usable range of center-of-gravity positions may be possible, which would serve to reduce the required tail area. This condition can be realized through use of a tail of low aspect ratio. Triangular plan forms of low aspect ratio are well adapted for use as tail surfaces for high-speed flight. These plan forms are structurally and aerodynamically suited to use as all-movable tail surfaces which would eliminate the possibilities of large trim and stability changes due to loss in elevator effectiveness. From a structural standpoint, the low aspect ratio enables a large depth for a monospar even for low values of section thickness ratio. From an aerodynamic standpoint, the triangular plan form has little aerodynamic-center shift and no large changes in lift-curve slope in going from subsonic to supersonic speeds. By way of comparison, a tail of high aspect ratio is advantageous for a tail-aft airplane, at least from the standpoint of stability.

At present there is very little experimental evidence to confirm the points set forth in the preceding discussion. German wind-tunnel tests have been made of a small-scale model (0.0354) of a canard-type missile known as the Rhärentochter III. This missile employs a sweptback

wing and an all-movable tail. Although the Rhientochter III does not represent a design intended for a man-carrying aircraft, the results of the wind-tunnel tests, which are reported in reference 5, show only small changes in trim and stability for the investigated Mach numbers of 0.6, 0.8, 0.9, and 1.45. This result qualitatively confirms the features of the canard discussed in the preceding paragraphs.

LOW-SPEED CHARACTERISTICS OF CANARD AIRPLANE AS  
COMPARED TO CONVENTIONAL AIRPLANE

Application of the canard-type arrangement to subsonic aircraft has been considered in the past. The absence of downwash and slipstream effects at the horizontal tail enables more accurate prediction of stability and control characteristics, and for a time some designers felt that the canard could be made to have maximum-lift characteristics superior to the tail-aft airplane. One reason that designers have favored the tail-aft arrangement is that simpler installation of the usual engine-propeller combination is afforded.

There is no evidence to indicate that the handling qualities of the canard at low lift coefficients should be unlike a tail-aft airplane having about the same proportions although the canard might require a somewhat greater vertical-tail area in order to provide adequate directional stability. If a high-fineness-ratio fuselage is used, a reasonable tail length will be provided even with the center of gravity slightly back of the fuselage midpoint, and it does not appear that the required increase in vertical-tail area would be enough to affect appreciably the over-all drag of the configuration.

Another aspect of flight at low lift coefficients that may merit consideration concerns the behavior of a canard airplane in gusts. Gust loads on a canard have been investigated and the results of this investigation are presented in reference 6. The results indicate that the pitching moment caused by the tail entering the gust before the wing is important and that normal accelerations in a gust are somewhat greater for a canard than for the tail-aft airplane due to the pitching tendency and due to the large tail loads. Comparison of test results for a canard model having an unswept wing with results for an equivalent tail-aft model shows that the higher accelerations for the canard were chiefly due to the tail load and that the wing loads of the two models were about the same. This result indicates that gust loads would have to be considered in the structural design of the tail of a canard airplane.

Spin-tunnel tests of a canard (reference 7) showed good recovery characteristics because the vertical tail is not blanketed by the horizontal tail in the spinning attitude.

There are several important stability and control problems associated with the operation of the canard at high lift coefficients. These problems are as follows:

- (1) The difficulty in obtaining satisfactory stalling characteristics
- (2) The difficulty in obtaining a design suitable for use of high-lift devices
- (3) The possibility of encountering very stable trim positions beyond the stall

Stalling characteristics.- The analysis presented in reference 8 shows that a canard airplane will have unsatisfactory stalling characteristics for any center-of-gravity position at which the wing stalls prior to the horizontal tail. Under this condition, a nose-up change in trim will occur at the stall and the variation of pitching moment with angle of attack beyond the stall will be unstable. Because of these unsatisfactory characteristics, a conclusion in reference 8 was that the aft center-of-gravity limit of the canard airplane should be dictated by the condition of simultaneous stalling of the wing and horizontal tail rather than by the condition of neutral stick-fixed stability. For center-of-gravity positions forward of this aft limit, the stalling characteristics of the canard should be satisfactory, at least from the standpoint of trim change and stability. The horizontal tail will stall prior to the wing, resulting in a nose-down trim change, and positive longitudinal stability will be maintained. By comparison, a tail-aft airplane will have a nose-down trim change and, usually, positive stability when the wing stalls before the tail, as is always the case, although instability may occur at the stall if sweptback wings are used. In general, the aft limit of center-of-gravity positions for the tail-aft airplane will be dictated by neutral stick-fixed stability.

The statements concerning the behavior of the canard at the stall when the horizontal tail stalls before the wing are substantiated by flight tests of the Focke-Wulf F19a "Ente," a German tail-first airplane. Results of these tests are reported in reference 9. This airplane was flown with large static margins (10 to 14 percent of the mean wing chord). The stall of the "Ente" was characterized by a gradual pitching in a nose-down direction until a slight nose-down attitude was attained. If the stick was held back throughout the stall, the airplane again pitched to a high angle of attack and the cycle was repeated. Gradual application of rudder at the stall resulted in spiraling of the airplane in a

slight nose-down attitude. At flight speeds where the horizontal tail of the Focke-Wulf F19a airplane was at high lift, tail stalling was produced by gusts which resulted in large-amplitude oscillations in pitch when flying in rough air at low speed. This characteristic may have an important bearing on the handling qualities of a canard during landings under gusty conditions but can possibly be remedied through use of a horizontal tail having a flat-topped curve of normal force against angle of attack.

The canard may have unsatisfactory stalling characteristics even though the tail stalls before the wing. This type of stall is characterized by a very rapid pitching of the airplane in a nose-down direction caused by the horizontal tail remaining in a stalled condition due to the pitching velocity. At present it is not definitely established whether this characteristic is severe enough in the canard to be unsatisfactory, and further experimental investigations are necessary. If this stalling characteristic does present a serious problem, it also might be remedied through use of a horizontal tail with a flat-topped curve of normal force against angle of attack. The triangular tail plan forms which have been suggested herein as suitable for use at high speeds have this characteristic type of normal-force variation. If this normal-force variation can be incorporated into the horizontal-tail design, the canard airplane might be made effectively stallproof.

In addition to these previous considerations, another effect which may have an important bearing on the behavior of the canard at the stall is that produced by the variation in tail wash at the wing. Premature tip stalling could result if a large upwash exists near the wing tips and downwash is present at the root. Tip stalling can result in severe rolling or in longitudinal instability of a sweptback wing. If a low-aspect-ratio tail is used, the region of large upwash from the tail will be well inboard from the wing tips, a condition which might improve the stalling characteristics of swept wings.

In order to eliminate the previously mentioned restriction on the usable center-of-gravity range of the canard airplane, the use of a free-floating horizontal tail with servotab control was suggested in reference 10 as a method for obtaining satisfactory stalling characteristics. As no variation of pitching moment with angle of attack is produced by this tail, the longitudinal stalling characteristics are dependent only on the pitching-moment variation produced by the wing-body combination. This arrangement for landing shows considerable promise. As mentioned previously, the floating tail probably has unsatisfactory characteristics at high speeds.

Maximum lift.- With the usable center-of-gravity range restricted in the proposed manner (in order to give the canard stability at the stall) the wing maximum lift is approached only at the aft

center-of-gravity limit. The loss in wing maximum lift is compensated to some extent by the large lift loads on the horizontal tail. The maximum lift of the wing of a tail-aft airplane usually can be safely attained throughout the usable center-of-gravity range, but the lift contribution from the horizontal tail is small and may be negative for forward center-of-gravity positions.

Another factor that may affect the lift capabilities of the canard airplane is the effect of tail wash in the vicinity of the wing. Although this effect is difficult to evaluate quantitatively, the discussion which follows serves to indicate its nature. As is well known, downwash will be present directly behind the tail of the canard while comparatively large values of upwash will exist behind the tail immediately outboard of the tail tips. This upwash diminishes rapidly with distance outboard of the tail tips. For a canard of usual geometry the wing span is fairly large compared to the tail span. In this case, the part of the wing near the root is in a region of downwash, a comparatively large upwash region exists near midspan, and small values of upwash are present near the wing tips. The magnitude of the tail wash is dependent on tail geometry and decreases with distance behind the trailing edge. The effect of tail wash on wing maximum lift is not only dependent on its magnitude at the wing but also on the spanwise progression of the wing stall. For example, if the wing stall progresses from tip to root, the presence of tail wash will transfer some of the lift load inboard from the tips which may prevent flow breakdown at the tips and thereby increase the maximum lift of the part of the wing outboard of the root downwash region. The downwash present near the root, however, decreases the lift contribution in that region. Similar reasoning indicates that the presence of tail wash is most undesirable from the standpoint of maximum lift when the initial flow breakdown on the wing occurs near midspan while tail wash is less serious if the initial stalling tendency occurs near the wing root. In general, the presence of tail wash would appear to result in some reduction in maximum lift. Gates in a study made in Great Britain of the high-lift characteristics of the canard concluded that this effect should be small.

In order to compare the maximum-lift characteristics of the canard, when restricted by the proposed aft center-of-gravity limit, with those for the tail-aft airplane (without regard to high-lift devices), the first-order equations for maximum trim lift coefficient  $C_{L_{ma}}$  and the

variation of  $C_{L_{ma}}$  with center-of-gravity position  $\frac{dC_{L_{ma}}}{d(x/c)}$  have been

derived for both configurations. Linear variations of aerodynamic parameters are assumed and the wing pitching moment at zero lift is neglected (symmetrical section). Differences in the dynamic pressure at the tail and in the free stream are neglected in the case of the

conventional airplane, and the effect of tail wash on the wing is neglected in the case of the canard airplane. As indicated previously, the equations for the canard may be somewhat optimistic because the tail wash is neglected.

For the canard, these equations were determined from the equation for equilibrium of pitching moments at the stall for an arbitrary center-of-gravity position. The equations were developed so that the position of the arbitrary center of gravity is expressed in chord lengths from the center-of-gravity position at which the wing and horizontal tail stall simultaneously (the assumed aft limit). These

equations for  $C_{L_{m_a}}$  and  $\frac{dC_{L_{m_a}}}{d(x/c)}$  are

$$C_{L_{m_a}} = \frac{C_{L_{m_t}} \frac{S_t}{S} \frac{l}{c}}{\frac{x}{c} + \frac{C_{L_{m_t}}}{(C_{L_{m_a}})_{x=0}} \frac{S_t}{S} \frac{l}{c}}$$

$$\frac{dC_{L_{m_a}}}{d(x/c)} = - \frac{C_{L_{m_a}}}{\frac{x}{c} + \frac{C_{L_{m_t}}}{(C_{L_{m_a}})_{x=0}} \frac{S_t}{S} \frac{l}{c}}$$

where

$$(C_{L_{m_a}})_{x=0} = C_{L_{m_{wb}}} + C_{L_{m_t}} \frac{S_t}{S}$$

and

$x/c$

center-of-gravity position in wing chord lengths from aft limit (positive forward)

$l/c$	distance in wing chord lengths between aerodynamic center of horizontal tail and aerodynamic center of wing-body combination
$S_t/S$	ratio of horizontal-tail area to wing area
$C_{L_{m_{wb}}}$	maximum lift coefficient of wing-body combination
$C_{L_{m_t}}$	maximum lift coefficient of horizontal tail

The foregoing equations show that the maximum trim lift coefficient of the canard airplane will decrease with forward movement of the center of gravity, but that the rate of decrease becomes less as the center of gravity moves forward. For a given value of  $C_{L_{m_{wb}}}$  the maximum lift

coefficient of the canard airplane for the center-of-gravity position where the wing and tail stall simultaneously may be increased by increasing  $C_{L_{m_t}}$  or the ratio  $S_t/S$ , and the rate of change of  $C_{L_{m_a}}$

with center-of-gravity position may be reduced by increasing the ratio  $l/c$  and, to a lesser extent, by increasing either  $C_{L_{m_t}}$  or  $S_t/S$ .

These equations also show that, with the aft center-of-gravity limit as specified, the maximum trim lift coefficient is independent of the lift-curve slopes of wing and tail. Variation of these lift-curve slopes serves only to change the location of the aft center-of-gravity limit with respect to the stick-fixed neutral point, and these parameters may be used to adjust the amount of longitudinal stability. The specified aft center-of-gravity limit will be ahead of the stick-fixed neutral point when the ratio of maximum lift coefficient to lift-curve slope for the horizontal tail is greater than this ratio for the wing-body combination. The lift-curve slope of the tail may be governed to some extent by the desirability of obtaining a high maximum lift coefficient of the tail.

For the tail-aft airplane where the aft center-of-gravity limit is determined by neutral stick-fixed stability, the equations for  $C_{L_{m_a}}$  and  $\frac{dC_{L_{m_a}}}{d(x/c)}$  were obtained from the equation for equilibrium of pitching

moments at the stall for an arbitrary center-of-gravity position and from the equation for neutral stability. The equations for  $C_{L_{m_a}}$

and  $\frac{dC_{L_{m_a}}}{d(x/c)}$  are

$$C_{L_{m_a}} = \frac{C_{L_{m_{wb}}} \frac{l}{c}}{\frac{x}{c} + \frac{C_{L_{\alpha_{wb}}} l}{C_{L_{\alpha_a}} c}}$$

$$\frac{dC_{L_{m_a}}}{d(x/c)} = - \frac{C_{L_{m_a}}}{\frac{x}{c} + \frac{C_{L_{\alpha_{wb}}} l}{C_{L_{\alpha_a}} c}}$$

where

$$C_{L_{\alpha_a}} = C_{L_{\alpha_{wb}}} + C_{L_{\alpha_t}} \left(1 - \frac{d\epsilon}{d\alpha}\right) \frac{S_t}{S}$$

$C_{L_{\alpha_{wb}}}$

variation of lift coefficient with angle of attack  
for wing-body combination

$C_{L_{\alpha_t}}$

variation of lift coefficient with angle of attack  
for horizontal tail

$\frac{d\epsilon}{d\alpha}$

variation in downwash angle at the horizontal tail  
with angle of attack

Comparison of these equations for the tail-aft airplane with the foregoing equations for the canard shows that the length parameters  $x/c$  and  $l/c$  produce similar effects in both cases, and at the aft center-of-gravity limit the ratio  $S_t/S$  also produces a similar effect. However, increasing  $S_t/S$  decreases the variation of  $C_{L_{m_a}}$  with center-of-gravity position for the canard arrangement, whereas the opposite

effect on this variation occurs for the tail-aft arrangement. A further indication from these equations is that the lift-producing capabilities of the canard may be superior to the tail-aft airplane when the center of gravity in both cases is at the aft limit, but the variation of  $C_{L_{ma}}$

with center-of-gravity position will be larger for the canard than for the tail-aft arrangement. The equations for the tail-aft airplane show that a high lift-curve slope of the horizontal tail is beneficial and that the presence of downwash at the tail is detrimental from the standpoint of maximum-lift characteristics.

In order to obtain a more quantitative comparison of the canard and the tail-aft airplane with regard to maximum lift, typical values of the aerodynamic parameters have been substituted in the preceding equations and values of  $C_{L_{ma}}$  have been computed as a function of center-of-gravity position for various values of the ratios  $S_t/S$  and  $l/c$ . Experimental data taken from reference 11 for a wing-body combination having a  $42^\circ$  sweptback wing of aspect ratio 4.01 were used as a basis for the computations for both the canard and the tail-aft arrangement. This wing-body combination had a lift-curve slope of about 3.6 per radian and a maximum lift coefficient of 1.1. Since the equations show advantages for using a high lift-curve slope of the tail for the tail-aft airplane, the same aerodynamic characteristics were assumed for the horizontal tail as for the wing. For the canard configuration, experimental data from tests of triangular plan forms (reference 12) were used as a basis for the aerodynamic characteristics of the horizontal tail, and an aspect ratio of 2 was selected because it provided the highest maximum lift coefficient (1.25). A value of  $d\epsilon/d\alpha$  of 0.4 was used in the computations for the tail-aft airplane.

Results of these computations are presented in figure 5. A decidedly superior maximum lift coefficient is indicated for the canard at rearward center-of-gravity positions, but because of the rapid decrease in  $C_{L_{ma}}$  with forward center-of-gravity movement, the usable center-of-gravity range may be limited. The magnitude of the range of superiority of the canard over the tail-aft airplane increases rapidly with increase in the ratio  $S_t/S$  and increases at a somewhat lesser rate with increase in ratio  $l/c$ . For typical values of  $S_t/S$  and  $l/c$  ( $\frac{S_t}{S} = 0.2$  and  $\frac{l}{c} = 3.5$ ), these computations show that the canard has superior maximum-lift characteristics over a center-of-gravity range of about 8 percent of the wing chord. For high values of tail length and tail area ( $\frac{S_t}{S} = 0.3$  and  $\frac{l}{c} = 4.5$ ), this range of superior lift characteristics is greatly

extended to 24 percent of the wing chord, whereas for small values of tail length and tail area  $\left(\frac{S_t}{S} = 0.1 \text{ and } \frac{l}{c} = 2.5\right)$  this range is limited to  $\frac{1}{2}$  percent. In consideration of the use of sweptback wings, the foregoing discussion on high-speed flight indicates that large tail lengths are possible for the canard, whereas the tail-aft airplane may be limited to comparatively short tail lengths. For example, if a value of  $l/c$  of 4.5 were possible for the canard, whereas the tail-aft arrangement was limited to a value of  $l/c$  of 2.5, a comparison on this basis shows a range of superior lift-producing capabilities for the canard of 14 percent of the wing chord with a typical tail-wing area ratio of 0.2.

Use of high-lift devices. - The adaptability of the canard airplane to the use of high-lift devices has been investigated by S. B. Gates, and the results of his analysis are presented in a British report. Gates concluded that considerably higher lift increments due to flap deflection could be handled by the tail-aft airplane than by the canard airplane. The comparatively poor characteristics of the canard in this respect result from the large nose-down pitching moment caused by the flap deflection because the center of gravity must be well ahead of the wing aerodynamic center in order to provide stability and even further ahead of the center of pressure due to flap deflection. A canard airplane having usual geometric proportions and aerodynamic characteristics would require an appreciably higher increment in tail lift coefficient to balance the pitching moment due to deflection of the wing flaps than the increment in wing lift coefficient obtained from the flaps. Gates felt that the best high-lift device would be used on the wing, and, therefore, the power of the tail could not be made large enough to take advantage of the highest lift increment possible.

Several features of a high-speed airplane may influence these conclusions. These features, favorable to the canard, are as follows:

- (1) The use of bodies of high fineness ratio and sweptback wings makes very large tail lengths possible for the canard airplane.
- (2) High-lift devices suitable for use on swept wings produce comparatively small increments in lift. (See reference 13.)
- (3) One of the most promising high-lift devices for swept wings, a combination of a leading-edge and a trailing-edge flap, has a center of pressure due to flap deflection near the wing aerodynamic center. (See reference 13.)

(4) Use of a horizontal tail of low aspect ratio positions the stick-fixed neutral point nearer the wing aerodynamic center, which would reduce the nose-down pitching moment for usual values of static margin.

When these possibilities are considered, the design charts prepared by Gates show that for reasonable magnitudes of airplane stability a horizontal tail of conventional size would be sufficiently powerful to handle the lift increments due to deflection of high-lift devices that are probable with swept wings.

The preceding analysis of stalling characteristics, however, places a further limitation on the canard airplane with regard to use of high-lift devices. Stalling characteristics were not considered in the analysis made by Gates, and therefore usable center-of-gravity positions back to the stick-fixed neutral point were assumed possible. The aft center-of-gravity limit proposed herein will generally result in greater than usual values of longitudinal stability. If the aft center-of-gravity limit is dictated by simultaneous stalling of wing and tail, the problem relating to high-lift devices may be stated more simply. The problem is that the canard airplane should be designed so that the lift-producing capabilities of the horizontal tail are never greater than those required to balance the pitching moment of the wing-body combination at maximum lift of the wing without high-lift devices. With this stipulated condition, increasing the lift-producing capabilities of the wing does not increase the maximum lift coefficient of the airplane.

Even though the aft center-of-gravity position is limited in the proposed manner, it may be possible to use high-lift devices to advantage, provided a nose-up pitching moment can be applied simultaneously with deflection of the high-lift device. The equation expressing the required magnitude of this nose-up pitching moment (expressed in terms of a tail lift increment) has been developed from the equations for equilibrium of pitching moments at the stall with the high-lift device retracted and deflected. At the proposed aft center-of-gravity limit this equation is

$$\frac{\Delta C_{L_{m_t}}}{C_{L_{m_t}}} = \frac{\Delta C_{L_{m_{wb}}}}{C_{L_{m_{wb}}}} \left( 1 + \frac{y/c}{d/c} \right)$$

where

$y/c$

distance in wing chord lengths from aerodynamic center of wing-body combination to center of pressure due to deflection of high-lift device (positive rearward)

- $d/c$  distance in wing chord lengths from aft center-of-gravity limit to aerodynamic center of wing-body combination (positive rearward)
- $\Delta C_{L_{m_{wb}}}$  increment in wing-body lift coefficient due to deflection of high-lift device
- $\Delta C_{L_{m_t}}$  increment in tail lift coefficient required to balance pitching moment due to deflection of high-lift device

The parameters  $C_{L_{m_t}}$  and  $C_{L_{m_{wb}}}$  are as previously defined, and the ratio  $d/c$  may be defined further as

$$\frac{d}{c} = \frac{l/c}{1 + \frac{C_{L_{m_{wb}}}}{C_{L_{m_t}}} \frac{S}{S_t}}$$

The foregoing equation indicates that at least a proportional increase in tail lift would be required to balance the lift increment on the wing. Actually the tail lift increment will have to be greater than proportional for high-lift devices whose center of pressure is behind the wing aerodynamic center as indicated by the term involving the ratio  $\frac{y/c}{d/c}$ . The relation expressing  $d/c$  indicates that large tail lengths and tail-wing area ratios are advantageous when use of high-lift devices is considered.

The best high-lift device indicated for swept wings from the tests of reference 13 had a value of  $y/c$  of about 0.08. This device was a combination of a leading-edge flap over the outboard portion of the wing and a split trailing-edge flap over the inboard portion of the wing. Assuming that the high-speed canard would have values of  $l/c$  of 4.5

and  $S_t/S$  of 0.2, the ratio  $\frac{y/c}{d/c}$  would be of the order of 0.1. There-

fore, if this device was used, the increment in tail lift coefficient required would be slightly greater than the corresponding increment in wing lift coefficient obtained from the high-lift device. The increases in lift coefficient obtained from this high-lift device, however, are of the order of 0.3 to 0.5, depending on the vertical location of the

wing on the fuselage. Attempts to obtain higher lift increments result in unsatisfactory characteristics of the wing itself, that is, longitudinal instability or poor lateral characteristics at high coefficients due to flow breakdown near the wing tips. In view of the low values of wing lift increment supplied by high-lift devices on swept wings, it appears possible to obtain the required increase in tail lift by simultaneously deflecting flaps on the tail. The necessary nose-up pitching moment might also be applied by a retractable auxiliary lifting surface located ahead of the center of gravity. Such a device would also reduce the longitudinal stability of the airplane causing a reduction in the required magnitude of the nose-up increment in pitching moment.

Assuming high-lift devices can be used advantageously on a canard, several features of wings employing large angles of sweep may limit their use even though good longitudinal and lateral stability characteristics of the wing itself can be maintained. For large angles of sweep, the lift-curve slope of the wing may be very low at high lift coefficients necessitating large changes in angle of attack for small increases in lift, and the ratio of lift to drag may be very low at high lift coefficients which results in steep glide paths and high vertical velocities under power-off conditions. Furthermore, operation appreciably below the maximum lift-to-drag ratio is shown in reference 11 to result in undesirable longitudinal control characteristics.

Trim positions beyond stall.- A third problem in connection with the low-speed characteristics of the canard airplane derives from flight tests of this type configuration in which a very stable trim position was encountered near  $90^\circ$  angle of attack. This occurrence is described in reference 14. Because of the high stability of this condition, recovery to ordinary flight conditions after this attitude is attained is very difficult. In the subject case this problem was eliminated by freeing the horizontal tail so that it could float with the relative wind whenever this attitude was encountered. Recovery might also be made by application of power. The foregoing discussion of stalling characteristics suggests that this problem might be eliminated without special devices or techniques if the usable center-of-gravity range is selected on the basis outlined herein. Stable stalling characteristics make it unlikely that such high angles of attack can be attained; and because the canard would have high longitudinal stability at low angles of attack, the possibility of a trim position at high angles of attack is more remote. Model tests would have to be made, however, to confirm this point.

#### CONCLUSIONS

A study has been made to determine the high-speed-flight characteristics of the canard airplane. This study shows that:

1. The canard configuration is well suited to the geometric arrangement of a wing-body combination with sweptback wings and a high-fineness-ratio body, particularly if the wing is mounted aft of the body maximum diameter in order to reduce the interference drag between wing and body. The effect on drag of the forward tail location is not known.

2. It is thought that the problem of buffeting might be reduced by locating the horizontal tail ahead of the wing although experimental evidence is needed to confirm this opinion.

3. Those changes in the longitudinal stability and control characteristics of an airplane in the transonic and supersonic speed ranges that are associated with changes in the flow at the horizontal tail can be avoided through use of the canard arrangement. Although flow changes produced by the tail of the canard will be present at the wing, general consideration of the effects would indicate that these effects should be smaller. At present there are not sufficient experimental results on canard configurations to verify this conclusion.

4. The large changes in longitudinal stability and trim of a tailless airplane which are caused by shift of the wing aerodynamic center are materially reduced for the canard configuration.

Several known problems associated with the low-speed characteristics of the canard were also investigated. The following conclusions were obtained:

1. The flying qualities of a canard airplane in rough air will probably be inferior to those of a conventional airplane.

2. In order to obtain satisfactory stalling characteristics for a canard airplane, the usable center-of-gravity range must be forward of the center-of-gravity position at which the wing and tail stall simultaneously. With this limitation, a simplified analysis indicates that the canard should have maximum-lift characteristics comparable to a tail-aft airplane at rearward center-of-gravity positions, but the decrease in maximum lift with forward movement of the center of gravity will be large and may limit the usable center-of-gravity range.

3. With the proposed aft center-of-gravity limit a rapid nose-down pitching motion may occur when a canard airplane stalls if the horizontal tail remains stalled due to the pitching velocity. If necessary, the severity of this motion might be reduced through use of a horizontal tail with a flat-topped normal-force curve.

4. Advantageous use of high-lift devices on the wing of the canard is possible only if the nose-down pitching moment due to the high-lift

device can be compensated by simultaneous deflection of flaps on the horizontal tail or a retractable auxiliary control surface located ahead of the center of gravity.

5. This study suggests that the possibility of encountering stable trim positions beyond the stall might be minimized if the usable center-of-gravity range is selected in the manner previously indicated.

Langley Aeronautical Laboratory  
National Advisory Committee for Aeronautics  
Langley Air Force Base, Va.

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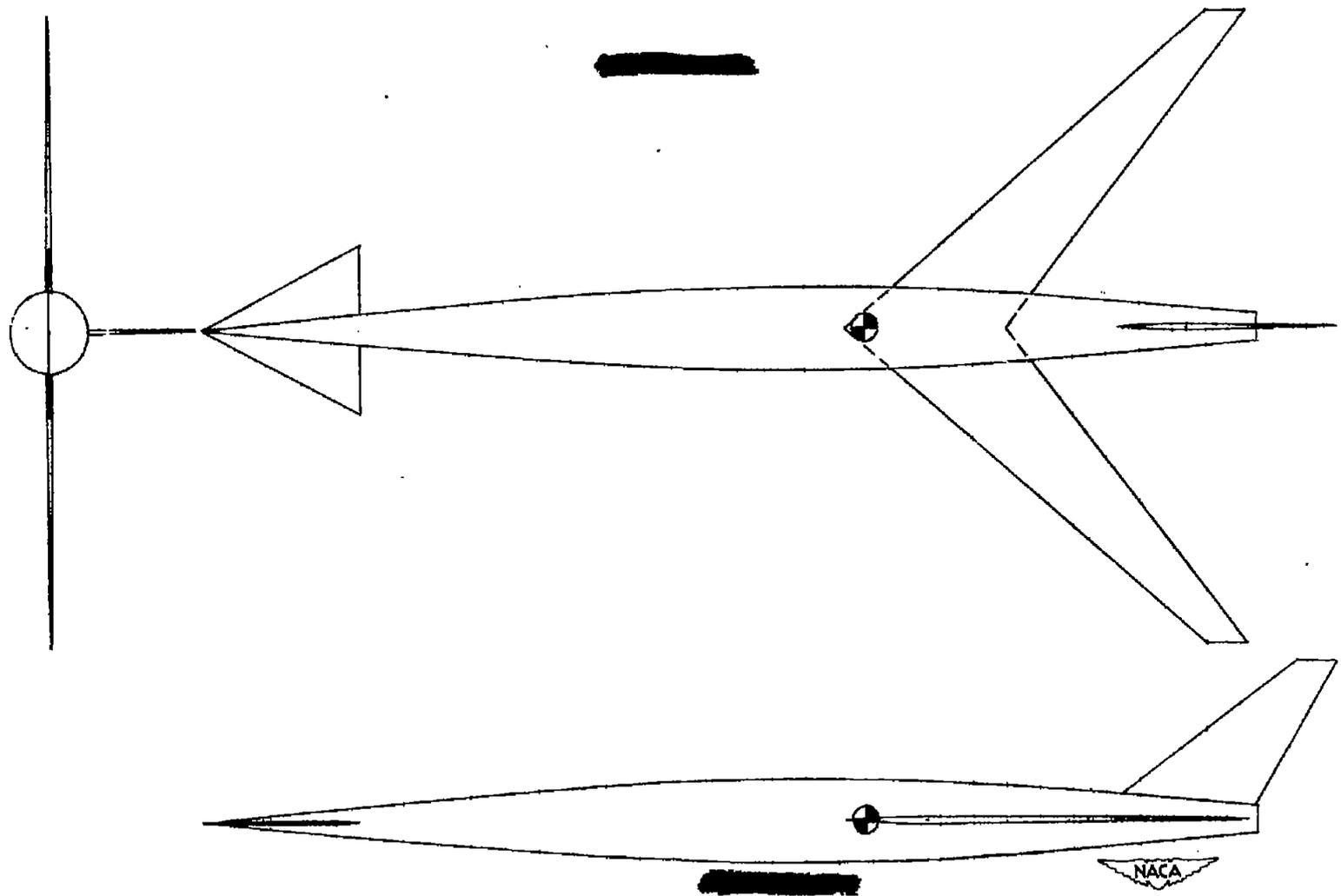


Figure 1.- Three-view drawing of canard configuration which embodies characteristics favorable to flight at transonic and supersonic speeds.

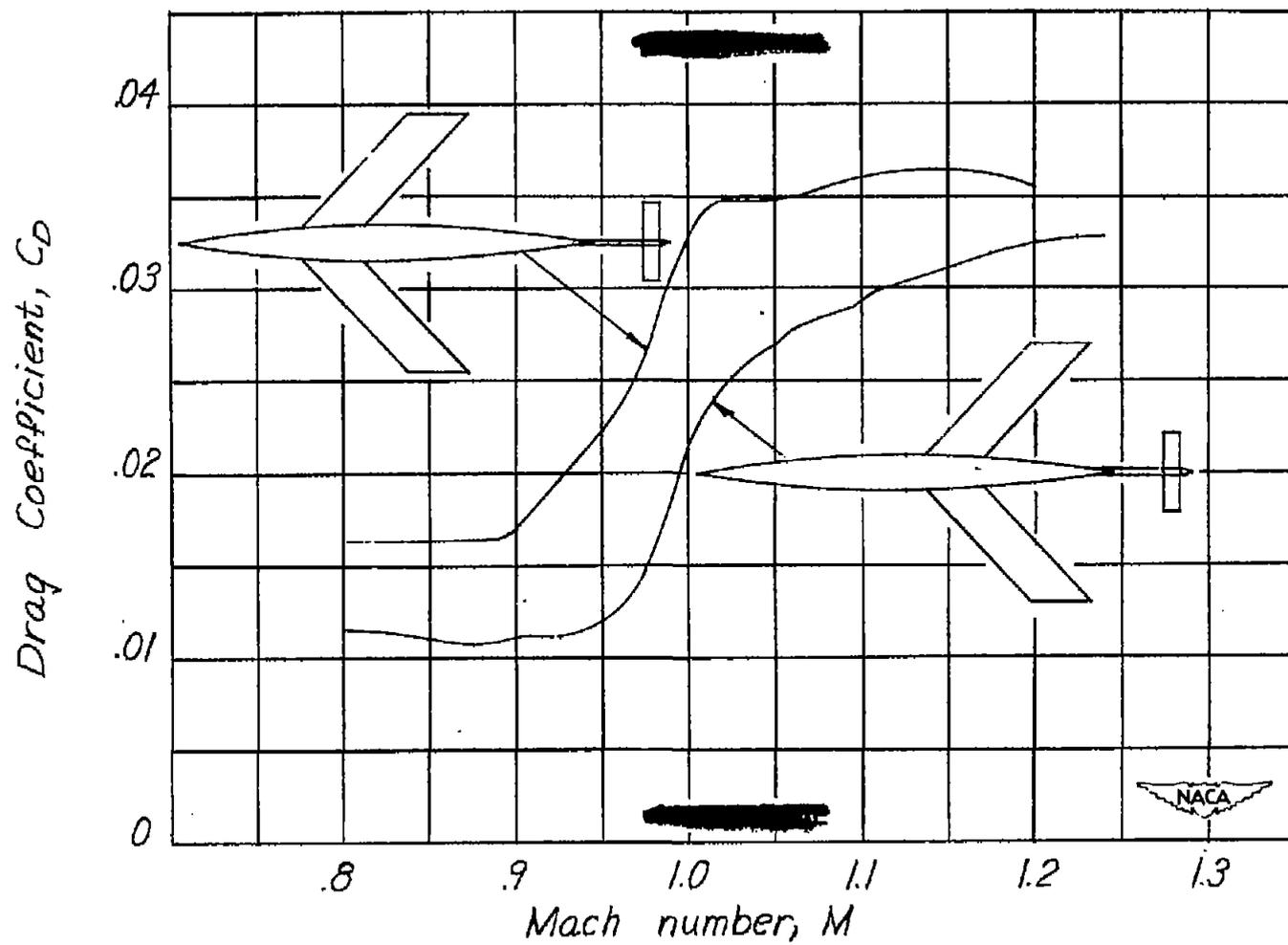


Figure 2.- Variation of total drag coefficient (based on wing plan area) with Mach number for two wing-body combinations differing only in location of wing.

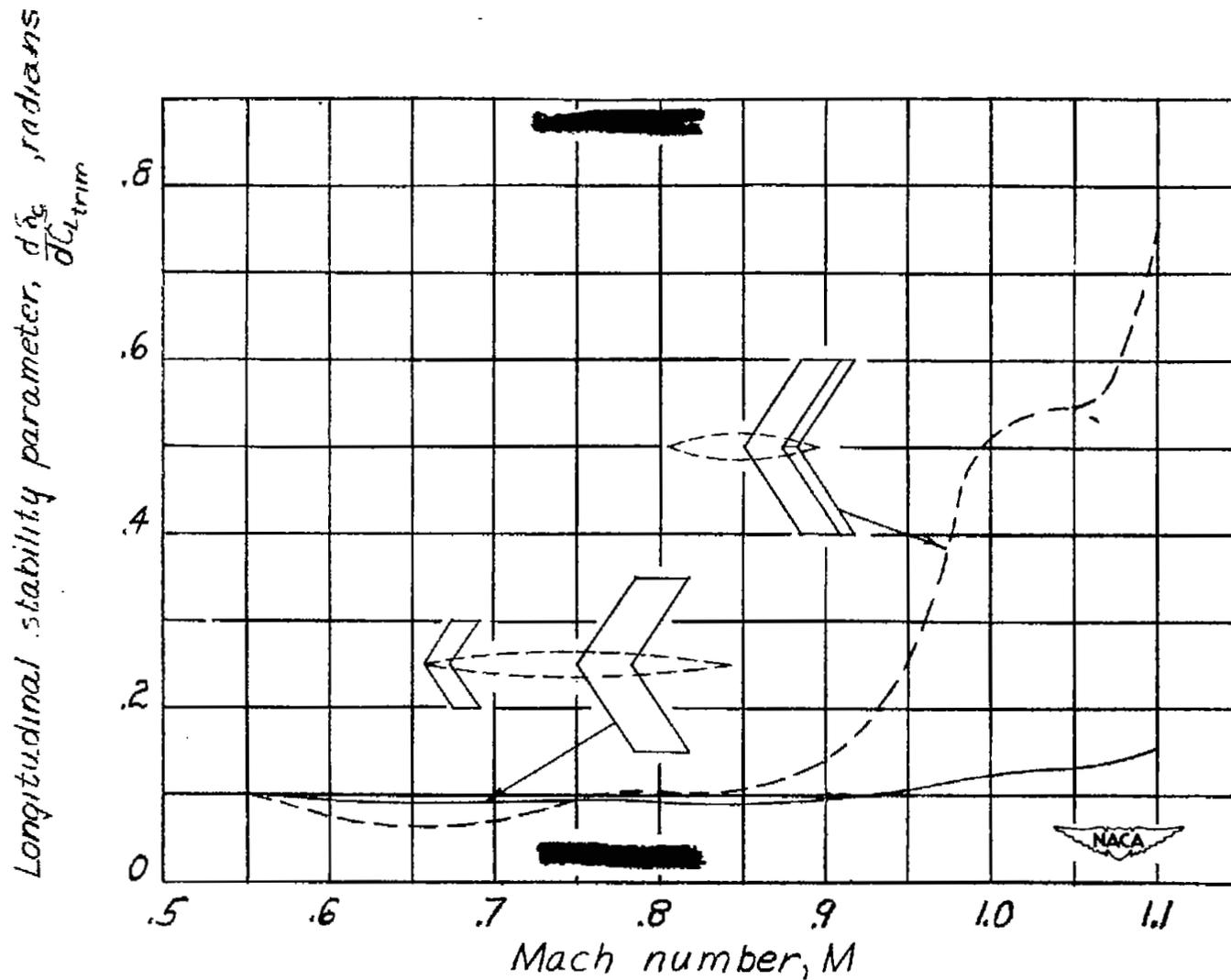


Figure 3.- Variation of longitudinal stability parameter  $\frac{d\delta_c}{dC_L}$  with Mach number for tailless configuration and for canard configuration.

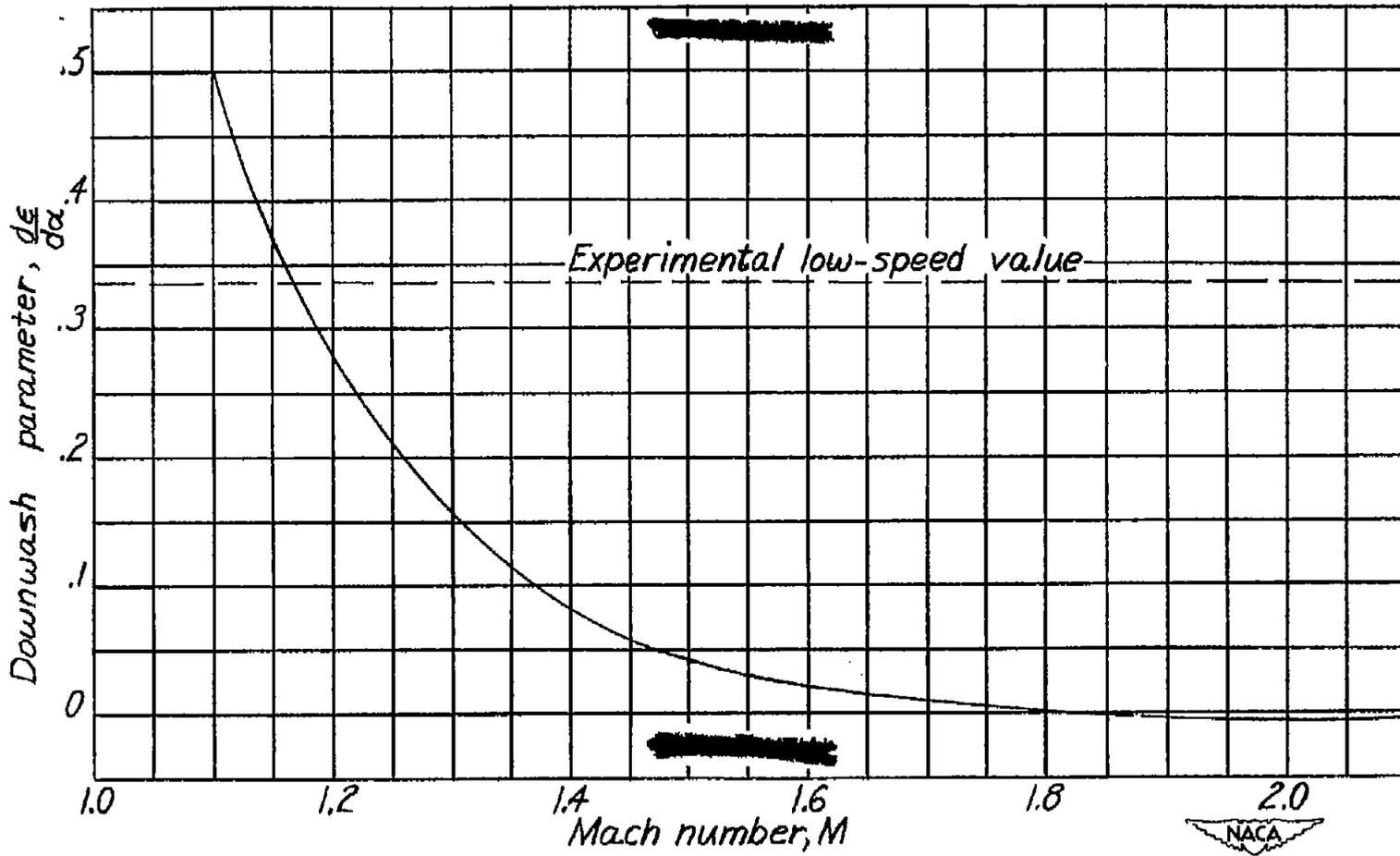


Figure 4.- Variation with Mach number of downwash at horizontal tail of conventional airplane with unswept wing.

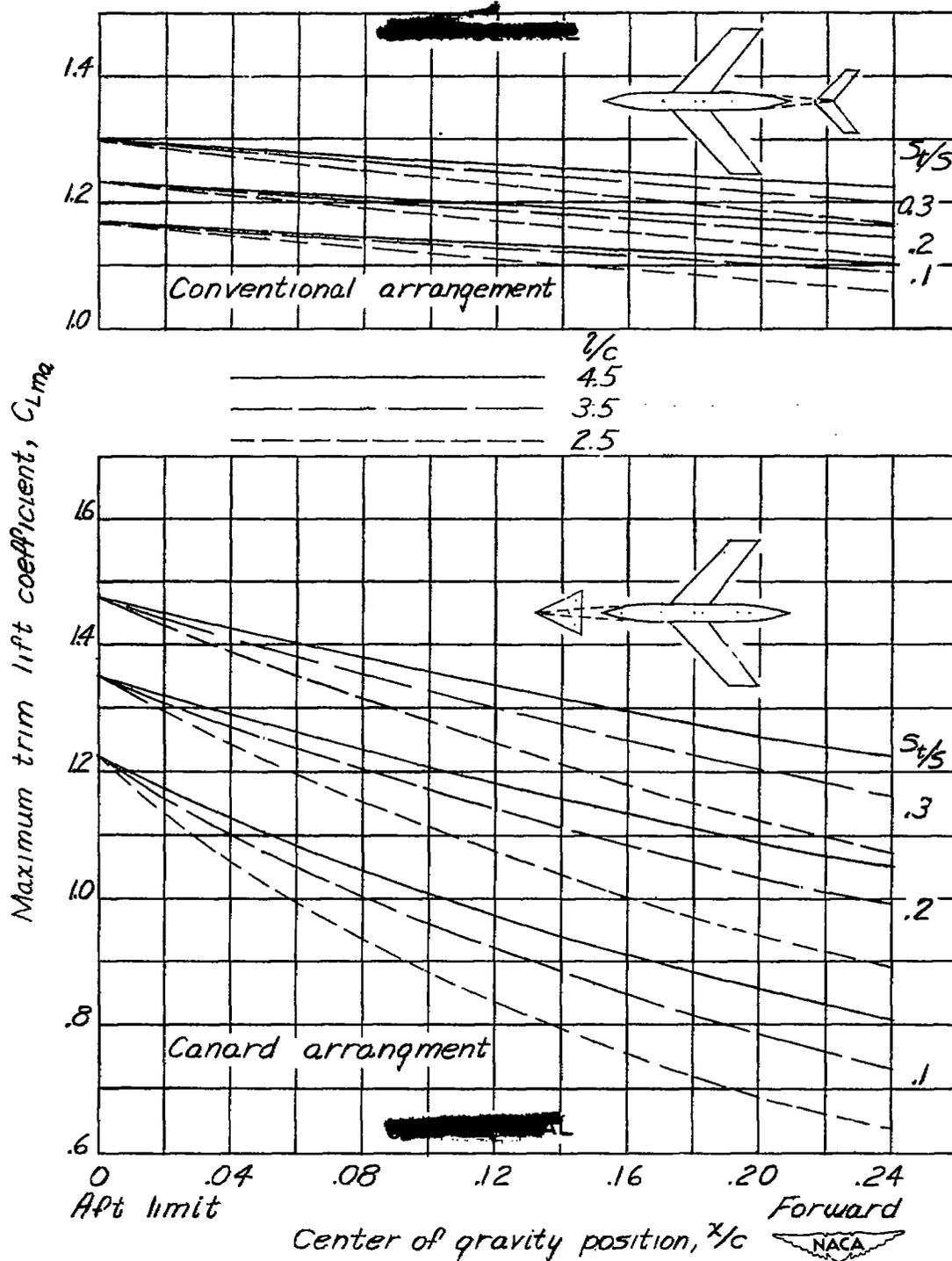


Figure 5.- Comparison of maximum trim lift coefficient of canard and conventional airplane. Maximum lift coefficient of wing-body combination is same for both configurations.