AN INVESTIGATION OF THE DIRECTIONAL AND LATERAL STICK-FIXED STABILITIES OF THE CANARD WITH END PLATE VERTICAL TAIL SURFACES

A Thesis
Presented to
the Faculty of the Graduate Division
Georgia Institute of Technology

In Partial Fulfillment
of the Requirements for the Degree
Master of Science in Aeronautical Engineering

By
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May 1956

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Approved:

Date Approved by Chairman: May 26, 1956

ACKNOWLEDGEMENTS

For their instruction and advice so necessary to the completion of this work, I wish to thank Professor Hurlbut W. S. LaVier, Professor Alan Y. Pope and Professor John J. Harper. To Dr. Nicholas Alexander, former Head of the Department of Aeronautics at the University of Rhode Island, whose faith and understanding prompted this work, I express my sincere gratitude and appreciation.

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LIST OF SYMBOLS

F	Froude's number
F_y, lb	side force
I_x, slug-ft^2	moment of inertia about the longitudinal axis
I_z, slug-ft^2	moment of inertia about the vertical axis
L, lb-ft	rolling moment
N, lb-ft	yawing moment
S, sq ft	total horizontal surface area
S_w, sq ft	wing area
S_t, sq ft	forward plane area
S_v, sq ft	vertical tail area
V, ft per sec	airstream velocity
W, lb	weight
a_w, per degree	wing lift curve slope
a_t, per degree	forward plane lift curve slope
b_w, ft	wing span
b_t, ft	forward plane span
b_v, ft	vertical tail span
c_w, ft	wing chord
c_t, ft	forward plane chord
c_v, ft	vertical tail chord
k_x, ft	radius of gyration about the longitudinal axis

k_z, ft	radius of gyration about the vertical axis
l_w, ft	distance measured along the longitudinal axis from the airplane center of gravity to the wing aerodynamic center
l_t, ft	distance measured along the longitudinal axis from the airplane center of gravity to the forward plane aerodynamic center
l_v, ft	distance measured along the longitudinal axis from the airplane center of gravity to the vertical tail aerodynamic center
m, slugs	mass
p, rad per sec	rolling velocity
$\dot{p}$, rad per sec^2	rolling acceleration
q, lb per sq ft	dynamic pressure
r, rad per sec	yawing velocity
$\dot{r}$, rad per sec^2	yawing acceleration
t, seconds	time
α_w, degrees	wing angle of attack
α_t, degrees	forward plane angle of attack
β, radians	angle of sideslip
$\dot{\beta}$, rad per sec	rate of change of angle of sideslip
Γ_w, degrees	wing dihedral angle
Γ_t, degrees	forward plane dihedral angle
λ, 1/seconds	damping factor
μ	airplane density factor

ρ, slugs per ft^3	atmosphere density
τ, seconds	time parameter
ϕ, radians	angle of roll
$\dot{\phi}$, rad per sec	rolling velocity
$\ddot{\phi}$, rad per sec^2	rolling acceleration
ψ, radians	angle of yaw
$\dot{\psi}$, rad per sec	yawing velocity
$\ddot{\psi}$, rad per sec^2	yawing acceleration
C_L	lift coefficient
C_{Lw}	wing lift coefficient
C_{Lt}	forward plane lift coefficient
C_d	drag coefficient
C_{dw}	wing drag coefficient
C_{dt}	forward plane drag coefficient
C_l	rolling moment coefficient
C_n	yawing moment coefficient
C_y	side force coefficient

SUMMARY

The purpose of the investigation was to clarify the directional and lateral stability problems of the canard configuration, ascertain if the problems could be overcome, and present reasons for the future development of the canard type airplane. Analytical methods were used to find the effect of the forward plane on the stability of the canard. Three configurations of forward plane were tested on a small canard free flight glider so as to compare the apparent stability with the analytical stability boundaries.

It was shown that a stable canard can be designed and efficiently operated as a large transport or bomber; that the major stability is the oscillatory boundary; that end plate vertical tail surfaces are necessary for proper stability in all flight positions.

CHAPTER I

INTRODUCTION

The present familiar, tail following, configuration of the airplane is fast approaching its limit of potential efficiency in the subsonic region of flight. Since this configuration has not been proved the most efficient arrangement of components, it is advisable that other configurations be studied.

One such alternate configuration is the canard. A canard is an airplane whose longitudinal stabilizing surface is located ahead of the main supporting surface. Thus the conventional stabilizer, on the canard, becomes a forward plane. The canard, or tail first, configuration possesses certain worthwhile features which, if exploited, could greatly enhance the performance of the large airplane. These features are (a) the direct utilization of all horizontal surfaces to lift, (b) the elimination of the stall, (c) the adaptability to power by atomic reactor.

Let us consider each of these advantages in order. Most airplanes are designed to have zero pitching moment with no elevator deflection at cruising conditions. In order to attain this zero pitching moment the airplane flies with a download on the tail. This download is analogous to added weight which serves to reduce the payload of the airplane. Any download, then, is an undesirable quantity. The canard flies with an upload on the balancing surface thereby adding to the load carrying capacity of the airplane.

When a conventional airplane reaches a critical angle of attack the wing stalls. This stall is an abrupt loss of lift due to the premature breaking away of the air flow from the wing. Since the wing is the only supporting surface of the conventional airplane, the stall produces a rapid loss in altitude until the airplane assumes an angle of attack below the critical angle and with the proper airspeed to maintain flight. The stall also can lead to a spin condition. Therefore the stall is undesirable. The canard can be designed so that the forward plane stalls at a critical angle below that of the wing. When the forward plane stalls the wing is not stalled. The nose tilts downward until the forward plane is no longer stalled. The canard loses little, if any, altitude since the main supporting surface has not lost its lift.

Work is being done to adapt atomic energy to the airplane. The fulfillment of this work will see an atomic reactor on the airplane. The human body must be shielded from the radiations of this reactor, but heavy shielding must be kept to a minimum. For purposes of stability the reactor must be located near the center of gravity of the airplane. A conventional transport or bomber has its center of gravity located quite close to the crew. The adaption of this type airplane to atomic power would require large amounts of shielding. The canard has its center of gravity far back from the normal crew stations so installation of an atomic reactor on the canard would require much less shielding. For a large airplane, this saving of weight would be of the order of thousands of pounds.

From just the foregoing points we see that the canard is a highly desirable airplane type. Unfortunately, the canard presents problems as well as benefits. Not the least of these problems is that of directional and lateral stabilities. Both directional and lateral stabilities must be considered at the same time since either one is affected by the other. The term spiral stability will be used in this paper to indicate directional and lateral stabilities and their interaction. Longitudinal stability does not seem to be much of a problem if care is taken to see that the maximum lift coefficient of the wing be greater than the maximum lift coefficient of the forward plane, and that the wing lift curve slope be greater than the forward plane lift curve slope.

There have been a few canards built and flown, but none were commercially successful. The reason for this was the lack of proper spiral stability in these airplanes. It is of interest to note that all of the canards attempted were small airplanes. Even the ones designed in recent years were one or two place machines.

It is not difficult to envisage the adverse effect upon stability that small size would give to a canard. Consider two equal moments one of which is due to a force applied at a moment arm, the other due to a smaller force acting at a longer moment arm. Assume that the two moments cause independent vibrations. If dampers are placed at each force in the two systems, it is easily seen that a smaller damping force is needed to damp out the vibrations caused by the small force, long moment arm combination. A canard has a relatively short moment arm between the center of gravity and the vertical tail. This situation necessitates the application of large tail forces for static stability and control. From the foregoing argument it is shown that with normal damping the canard will tend toward abnormally large oscillations in yaw. Shorter moment arms of smaller canards would aggravate these oscillations. Another way to visualize the effect of size on dynamic stability is as follows. Roughly speaking, the dynamic oscillations are caused by the moments of inertia, and the damping of these oscillations is due to surface size. Consider a moment of inertia, I, about any given axis and a surface placed in such a manner as to damp oscillations about this axis. Since $I = m k^2$, moment of inertia can be expressed as a mass times a $(\text{length})^2$. Then for a given mass, I, is proportional to $(\text{length})^2$. Now surface effect, or damping, increases as the area of the surface times its distance to the center of gravity, or as $(\text{length})^3$. Therefore, the damping due to an increase in size will far overweigh the inertia increase due to larger size.

CHAPTER II

STABILITY ANALYSIS

The analysis of the spiral stability of the canard is based upon the formulation of a hypothetical canard. This hypothetical canard is chosen, in the light of the foregoing arguments, to be of the size of the XC-99. The specifications of the XC-99 appear in Table 4. The purpose of the analysis is to obtain a physical picture of the role played by the forward plane in the spiral stability of the canard.

The assumption on which the analysis is based is that any lateral, directional, or cross stability derivatives in which the wing is involved is a sum of the components of both the wing and the forward plane. This assumption seems logical since both surfaces produce, about the same axes, moments which are certainly the sum of the moments created by the wing and the forward plane. In the conventional configuration, the horizontal tail produces negligible rolling and yawing moments. These moments produced by the forward plane of a canard cannot be neglected since the higher loads carried by this surface can cause considerable moment when they are unsymmetrically distributed.

The steps in the analysis are as follows:

(a) The hypothetical canard is formulated.

(b) The stability derivatives are determined with $C_{n\beta t}$ and $C_{l\beta t}$ kept as variables.

(c) The coefficients of the stability quartic are solved for in terms of $C_{n\beta t}$ and $C_{l\beta t}$.

(d) Routh's discriminant is found in terms of $C_{n\beta t}$ and $C_{l\beta t}$.

(e) The oscillatory boundary and the divergence boundary are plotted as functions of $\mu C_{n\beta t}$ and $\mu C_{l\beta t}$.

The specifications for the hypothetical canard are laid out in Fig. 1. Since all the stability derivatives can be varied on any airplane by changing the dihedral angles, fuselage shape, fillets, etc., the calculation of some derivatives is based on formulas which give desirable values of these derivatives. The formulas listed below are used for the forward plane values as well as for those of the wing by substituting forward plane subscripts in place of wing subscripts.

$$C_{n\beta w} = 0.0005 \left[\frac{W}{b^2}\right]^{\frac{1}{2}}$$

$$C_{l\beta w} = -\frac{C_{n\beta w}}{2}$$

C_{lpw} estimated

$$C_{l\,rw} = \frac{C_{Lw}}{4}$$

$$C_{npw} = -\frac{C_{Lw}}{8}$$

$$C_{n_{rw}} = -\frac{C_{dw}}{3} - 2\,a_v\,\frac{S_v}{S_w}\,\frac{l_v^{\,2}}{b_w^{\,2}}$$

$C_{y\beta w}$ estimated

Table 1 lists the values of the stability derivatives as well as the mass characteristics necessary for the solutions of the quartic coefficients. The stability quartic is:

$$A\lambda^4 + B\lambda^3 + C\lambda^2 + D\lambda + E = 0$$

The equations for the coefficients are:[1]

$$A = 1$$

$$B = -\frac{1}{2}\left(\frac{C_{nr}}{J_z} + \frac{C_{lp}}{J_x} + C_{y\beta}\right)$$

$$C = \frac{1}{4J_xJ_z}(C_{nr}C_{lp} - C_{lr}C_{np}) - \frac{C_{y\beta}}{4}\left(\frac{C_{nr}}{J_z} + \frac{C_{lp}}{J_x}\right) + \frac{\mu C_{n\beta}}{J_z}$$

$$D = -\frac{\mu}{2J_xJ_z}(C_{n\beta}C_{lp} - C_{l\beta}C_{np}) - \frac{\mu}{2J_x}C_{Lw}C_{l\beta}$$

$$- \frac{C_{y\beta}}{8J_xJ_z}(C_{lp}C_{nr} - C_{lr}C_{np})$$

$$E = \frac{\mu C_{Lw}}{4J_xJ_z}(C_{l\beta}C_{nr} - C_{n\beta}C_{lr})$$

The assumption that the stability derivatives are the sums of the components of the wing and forward plane alter the equations to read:

---

[1]Perkins, C. D. and R. E. Hage, Airplane Performance Stability and Control, New York: Wiley, London: Chapman & Hall, 1940, p. 427.

$$A = 1$$

$$B = -\frac{1}{2}\left[\frac{(C_{nrw} + C_{nrt})}{J_z} + \frac{(C_{lpw} + C_{lpt})}{J_x} + (C_{y\beta w} + C_{y\beta t})\right]$$

$$C = \frac{1}{4\,J_x J_z}\left[(C_{nrw} + C_{nrt})\,(C_{lpw} + C_{lpt})\right.$$

$$\left. - (C_{lrw} + C_{lrt})\,(C_{npw} + C_{npt})\right] - \frac{(C_{y\beta w} + C_{y\beta t})}{4}$$

$$\left[\frac{(C_{nrw} + C_{nrt})}{J_z} + \frac{(C_{lpw} + C_{lpt})}{J_x}\right] + \frac{\mu(C_{n\beta w} + C_{n\beta t})}{J_z}$$

$$D = -\frac{\mu}{2J_x J_z}\left[(C_{n\beta w} + C_{n\beta t})\,(C_{lpw} + C_{lpt}) - (C_{l\beta w} + C_{l\beta t})\right.$$

$$\left.(C_{npw} + C_{npt})\right] - \frac{\mu}{2J_x}\,C_{Lw}\,(C_{l\beta w} + C_{l\beta t}) - \frac{(C_{y\beta w} + C_{y\beta t})}{8\,J_x\,J_z}$$

$$\left[(C_{lpw} + C_{lpt})\,(C_{nrw} + C_{nrt}) - (C_{lrw} + C_{lrt})\,(C_{npw} + C_{npt})\right]$$

$$E = \frac{\mu\,C_{Lw}}{4J_x\,J_z}\left[(C_{l\beta w} + C_{l\beta t})\,(C_{nrw} + C_{nrt})\right.$$

$$\left. - (C_{n\beta w} + C_{n\beta t})\,(C_{lrw} + C_{lrt})\right]$$

Substitution of the values of the stability derivatives gives:

$$A = 1$$

$$B = -\frac{1}{2}\left(-\frac{0.0206}{0.290} - \frac{1.04}{0.053} - 0.00026\right)$$

$$C = \frac{1}{4\,(0.053)\,(0.290)}\left[(-0.0206)\,(-1.04) - (0.1375)\,(-0.0688)\right]$$

$$-\frac{0.00026}{4}\left(-\frac{0.0206}{0.290} - \frac{1.04}{0.053}\right) + \frac{6.81\,(0.00112 + C_{n\,\beta\,t})}{0.290}$$

$$D = -\frac{6.81}{2\,(0.053)\,(0.290)}\Big[(0.00112 + C_{n\,\beta\,t})\,(-1.04)$$

$$-\,(-0.00056 + C_{1\,\beta\,t})\,(-0.0688)\Big]$$

$$-\frac{6.81}{2\,(0.053)}\,(0.25)\,(-0.00056 + C_{1\,\beta\,t}) - \frac{0.00026}{8\,(0.053)\,(0.290)}$$

$$\left[(-1.04)\,(-0.0206) - (0.1375)\,(-0.0688)\right]$$

$$E = \frac{6.81\,(0.25)}{4\,(0.053)\,(0.290)}\Big[(-0.00056 + C_{1\,\beta\,t})\,(-0.0206)$$

$$-\,(0.00112 + C_{n\,\beta\,t})\,(0.1375)\Big]$$

which expand to:

$$A = 1$$

$$B = 9.85$$

$$C = 23.48\,C_{n\,\beta\,t} + 0.5301$$

$$D = 230.4\,C_{n\,\beta\,t} - 0.73\,C_{1\,\beta\,t} + 0.2753$$

$$E = 3.806\,C_{n\,\beta\,t} + 0.57\,C_{1\,\beta\,t} + 0.003944$$

The equation:

$$E = 0$$

is the divergence boundary of the airplane. Routh's discriminant, R, set equal to zero is the oscillatory boundary:

$$R = B\,C\,D - A\,D^2 - B^2\,E = 0$$

The graphs of these equations are usually plotted with $\mu C_{n\beta}$ as ordinate and $\mu C_{l\beta}$ as abscissa. In order to show the effect of the forward plane, the foregoing equations provide graphs of the boundaries with $\mu C_{n\beta\,t}$ as ordinate and $\mu C_{l\beta\,t}$ as abscissa.

The equation:

$$R = B\,C\,D - A\,D^2 - B^2\,E = 0$$

is expanded as follows:

$$(9.85)\,(23.48\,C_{n\beta\,t} + 0.5301)\,(230.4\,C_{n\beta\,t} - 0.73\,C_{l\beta\,t} + 0.2753) - (230.4\,C_{n\beta\,t} - 0.73\,C_{l\beta\,t} + 0.2753)^2 - (9.85)^2\,(3.806\,C_{n\beta\,t} + 0.57\,C_{l\beta\,t} + 0.003944) = 0$$

$$300\,(C_{n\beta\,t})^2 + 770\,C_{n\beta\,t} + 181.4\,C_{n\beta\,t}\,C_{l\beta\,t} - 55\,C_{l\beta\,t} + 0.981 = 0$$

$$(C_{n\beta\,t})^2 + 2.566\,C_{n\beta\,t} + 0.605\,C_{n\beta\,t}\,C_{l\beta\,t} - 0.1833\,C_{l\beta\,t} + 0.00327 = 0$$

This equation is plotted by assuming values of $C_{n\beta\,t}$ and solving for $C_{l\beta\,t}$. A tabular solution is the most expedient method. Similarly, the equation:

$$E = 3.806\,C_{n\beta\,t} + 0.57\,C_{l\beta\,t} + 0.003944 = 0$$

may be written

$$C_{l\beta t} + 6.68\ C_{n\beta t} + 0.00692 = 0$$

and plotted by the same method.

CHAPTER III

EXPERIMENTAL PROCEDURE

The experimental phase of the investigation was designed to show the effect of the dihedral of the forward plane on the spiral stability of the canard. To this purpose a free flight glider was built with three interchangeable forward planes: (a) dihedral equal to that of the wing, (b) dihedral greater than that of the wing, (c) no dihedral. The model was scaled down in planform from the hypothetical canard. Specifications of the model are shown in Table 3.

It was impossible to fly the model at the same Reynold's number as the prototype, but since Reynold's number is more of a criterion for flow patterns than for stability oscillations this discrepancy is of little consequence. The two important parameters that had to be observed are airplane density factor, μ , and Froude's number, F . These parameters inter-relate airplane mass, velocity, characteristic length, and air density. Although Froude's number is used principally as a criterion for similar wave motion, the basis for this use is that wave motion is the result of the interaction between gravity forces and inertia forces of a fluid. The dynamics of an airplane is also the result of the interaction between gravity forces and inertia forces. Therefore, it may be concluded that Froude's number is a parameter for dynamic similarity. For the hypothetical canard:

$$\mu = \frac{m}{S_w \; b_w} = \frac{265{,}000}{(32.2)\;(0.0011)\;(4775)\;(230)}$$

$$\mu = 6.81$$

$$F = \frac{V}{\sqrt{g \; b_w}} = \frac{635}{\sqrt{(32.2)\;(230)}}$$

$$F = 7.38$$

For the model:

$$\mu = 6.81 = \frac{W}{(32.2)\;(0.002378)\;\left(\frac{13}{144}\right)\left(\frac{12}{12}\right)}$$

$$W = 0.047 \text{ lb} = 0.75 \text{ oz.}$$

$$F = 7.38 = \frac{V}{(32.2)\;\left(\frac{12}{12}\right)}$$

$$V = 41.9 \text{ fps}$$

Thus the model's 0.75 oz and 41.9 fps velocity is equivalent dynamically to the prototype's 265,000 lb and 635 fps velocity.

The flight tests were carried out as follows. With the desired forward plane in place, the model was hand launched in a straight glide from a height of approximately five feet. Oscillations of the model were observed. Moving pictures were taken of the model in flight. Since dihedral is, in effect, $C_{l_{\beta t}}$, it was possible to correlate the apparent stability of the model with the stability graph.

CHAPTER IV

RESULTS

1. Analytical

Equating E = 0:

C	- C
0.0	0.0481
0.00681	0.0925
0.03405	0.2740
0.06910	0.5020
0.1362	0.956
0.2043	1.390
0.2724	1.853
0.3405	2.320

Equating R = 0:

-0.0681	0.8015

For all practical limits of $\mu C_{l_{\beta t}}$, R = 0 can be considered to be linear.

2. Experimental

(a) With the dihedral of the forward plane equal to that of the wing, the model exhibited stable flight with a slight tendency to oscillate in yaw; (b) with the dihedral of the forward plane greater than that of the wing, the model exhibited marked tendencies toward oscillatory instability; (c) with no dihedral in the forward plane, the model exhibited no undue oscillatory or spiral instabilities. Sketches of the flight paths may be seen in Fig. 4.

CHAPTER V

DISCUSSION

The spiral stability investigation undertaken herein was based on dynamic stability equations, while static stability seems to have been neglected. Actually, a static stability investigation is somewhat misleading since it is based on the forward plane's having no effect in roll or yaw. While an accurate factor may be applied to give the effect of the forward plane of the canard in roll, any dihedral of the forward plane combined with the long moment arm creates an effective vertical tail area forward of the center of gravity. This makes an accurate static stability analysis impossible without individual wind tunnel tests.

The stability graph, Fig. 2, shows the boundaries between which the forward plane gives stability. Outside the divergence boundary, $E = 0$, the airplane is spirally unstable while outside the oscillatory boundary, $R = 0$, the airplane has Dutch roll instability. The solid lines are these boundaries for the forward plane of the hypothetical canard and the dashed lines are the boundaries for a typical conventional airplane.

At first glance, from the standpoint of static spiral stability, it would seem that the dihedral of the forward plane should be greater than that of the wing in order to insure an upward motion of the nose when the canard recovers in roll. From the dynamic stability analysis it is seen that the reverse is true. With the effective tail area, due to the dihedral of the forward plane, ahead of the center of gravity, $C_{n\beta t}$ drops sharply to the oscillatory boundary and beyond. This instability showed prominently in the flight of the model which had more dihedral in the forward plane than in the wing. As the dihedral of the forward plane decreased, the stability of the model increased thus strengthening the assumptions of the stability analysis.

For oscillatory stability it is obvious that $\mu C_{n\beta t}$ should be held positive since the oscillatory boundary is close to the $-\mu C_{l\beta t}$ axis. Dihedral in the forward plane, then, is detrimental to oscillatory stability because dihedral in the forward plane is equivalent to a vertical tail component ahead of the center of gravity. This component times its moment arm subtracts from the vertical tail times its moment arm, thus reducing $\mu C_{n\beta t}$. The reduction in $\mu C_{n\beta t}$ brings the canard close to the oscillatory boundary and, possibly, outside it.

In order to prevent oscillatory instability $\mu C_{n\beta t}$ requires little or no dihedral in the forward plane as well as a high product of vertical tail area times its moment arm. The value of $\mu C_{l\beta t}$ has a minimum negative value of about -0.04. The maximum negative value of $\mu C_{l\beta t}$ is limited by the rate of roll desired by the designer. Enough damping in roll must be incorporated in the airplane, though, to insure stability. It was assumed that $C_{l\beta}$ is the sum of $C_{l\beta t}$ and $C_{l\beta w}$. Now $C_{l\beta t}$ is equivalent to forward plane dihedral which is undesirable; therefore, all, or most all, of $C_{l\beta}$ must be $C_{l\beta w}$. Also the maximum negative value of $\mu C_{l\beta t}$ is severely restricted.

To be spirally unstable, or divergent, the canard must have a very high $\mu C_{n_{\beta t}}$. It is improbable that this high $\mu C_{n_{\beta t}}$ can be attained. The condition would require a very high product of vertical tail area times its moment arm, and a canard's short vertical tail moment arm precludes such a high product. Therefore, the problem of stability, as far as the forward plane is concerned, is the oscillatory boundary.

At all times, the model seemed to be far from the divergence boundary in contrast to the conventional airplane which operates at the divergence boundary. This bears out the analytical results. It is seen that a relationship exists between the dihedral of the forward plane and the area of the vertical tail, and an increase or decrease in one engenders a corresponding increase or decrease in the other.

The end plate vertical tail is the logical way to assign vertical tail area to the canard. It is unaffected, to all practical intents, by the downwash of the forward plane, wing wake, and propeller wash if that means of propulsion is used. Rudder control could utilize the rudder drag as well as side force due to lift of the rudder, and would be powerful enough to permit control by the deflection outwards of the individual rudders while simultaneous deflections of both rudders would act as an aerodynamic brake. If a single dorsal tail be used on a canard, it will be in the turbulent flow over the wing at high angles of attack. Under landing conditions, rudder control would be seriously limited; hence arises again the necessity for splitting the vertical tail area and locating it at the wing tips.

The effect of end plates has been studied by Mangler (2), Reid (3) and Hemke (4) among others. A comparison of their reports yields the following points of agreement: (a) the reduction of the induced drag exceeds the frictional drag of the end plates for all but small values of the lift coefficient; (b) moving the end plate up from the symmetrical position results in a slight increase in the total lift, an increase in the moment of the end plate about its attachment, and an increase of directional control.

The reduction of the induced drag of a heavy airplane is most advantageous. End plates are effective induced drag reducers for all but small values of the lift coefficient. The large airplane flies at a lift coefficient outside this small range and would profit by the utilization of end plates.

Although the canard has been considered heretofore as a large airplane, some limit should be put on the distance between the aerodynamic centers of the two horizontal surfaces. From a practical viewpoint, this distance should be approximately sixty-five per cent of the wing span. This arbitrary figure allows long moment arms while keeping the fuselage below wasteful proportions.

The canard can be so designed as to prevent a stall. It is interesting to note that this feature would make a stalled landing impossible. However, it has been the practice to land large airplanes with the airspeed considerably above that which would cause a stall. The landing procedure would not be altered for land based canards. A carrier based canard would be impractical from the standpoints of both landing procedure and large size. The canard lends itself nicely to the tricycle landing gear.

All transport or bomber aircraft, in service today, rely on wing flaps to increase the lift coefficient for landings and take-offs. This increase of the lift coefficient causes a corresponding increase in the diving moment about the center of gravity. For a conventional airplane, the center of gravity is located quite near the aerodynamic center; the moment produced by the increased lift coefficient is small. The canard has its center of gravity at some distance from the wing aerodynamic center and the diving moment produced by a lowered wing flap would be of appreciable magnitude. Of course, a flapped forward plane might help the situation somewhat, but it also could well cause considerable turbulence and buffeting of the airplane.

A possible solution to this problem is to incorporate boundary layer suction into the forward plane. It is known that boundary layer suction alone can double the lift coefficients which are attained with flaps. A combination of boundary layer suction on the forward plane and flaps on the wing can increase the lift coefficient while maintaining longitudinal stability if the increase in total lift of the forward plane times its distance to the center of gravity is equal, or nearly equal, to the same product of the wing.

$$\text{Lift, } L = C_L \frac{\rho}{2} S V^2$$

Since $\frac{\rho}{2} V^2$ is the same for the wing and the forward plane, for a negligible increase in diving moment:

$$\Delta C_{Lt} \; S_t \; l_t = \Delta C_{Lw} \; S_w \; l_w$$

For the hypothetical canard:

$$\Delta C_{Lt} = \Delta C_{Lw} \left(\frac{S_w}{S_t}\right)\left(\frac{l_w}{l_t}\right) = \Delta C_{Lw} \left(\frac{4775}{980}\right) \left(\frac{40}{112.5}\right)$$

$$\Delta C_{Lt} = 1.732 \; \Delta C_{Lw}$$

With boundary layer suction on the forward plane, $\Delta C_{Lt} = 1.732 \; \Delta C_{Lw}$ can be attained, thus insuring longitudinal stability at high values of the lift coefficient.

CHAPTER VI

CONCLUSIONS

1. A directionally and laterally stable canard can be built and efficiently operated.

2. The major stability problem is the oscillatory boundary, since the vertical tail area cannot be increased indiscriminately without adding undue drag.

3. All, or most all, of the necessary dihedral should be built into the wing with little or no dihedral in the forward plane.

4. Moment arms should be as long as is practicable.

5. End plate vertical tails are advantageous to the canard.

A P P E N D I X

Table 1

Mass Characteristics and Stability Derivatives of the Hypothetical Canard

W/S	55.5 lb/sq ft	μ	6.81
b_w	230.0 ft	k_x	37.4
ρ	0.0011	k_z	87.5
V	635.0 ft/sec	J_x	0.053
C_L	0.25	J_z	0.290

$C_{n\beta w}$	0.00112
$C_{n\beta t}$	variable
$C_{l\beta w}$	-0.00056
$C_{l\beta t}$	variable
C_{lpw}	-0.54
C_{lpt}	-0.50
C_{lrw}	0.0625
C_{lrt}	0.0750
C_{npw}	-0.0313
C_{npt}	-0.0375
C_{nrw}	-0.00861
C_{nrt}	-0.02035
$C_{y\beta w}$	0.000208
$C_{y\beta t}$	-0.000052

Table 2

Specifications of the Hypothetical Canard

b	230.0 ft.	b	98.0 ft.
c	20.8 ft.	c	10.0 ft.
S	4775 sq. ft.	S	980 sq. ft.
W	265,000 lb.	S	700 sq. ft.

Table 3

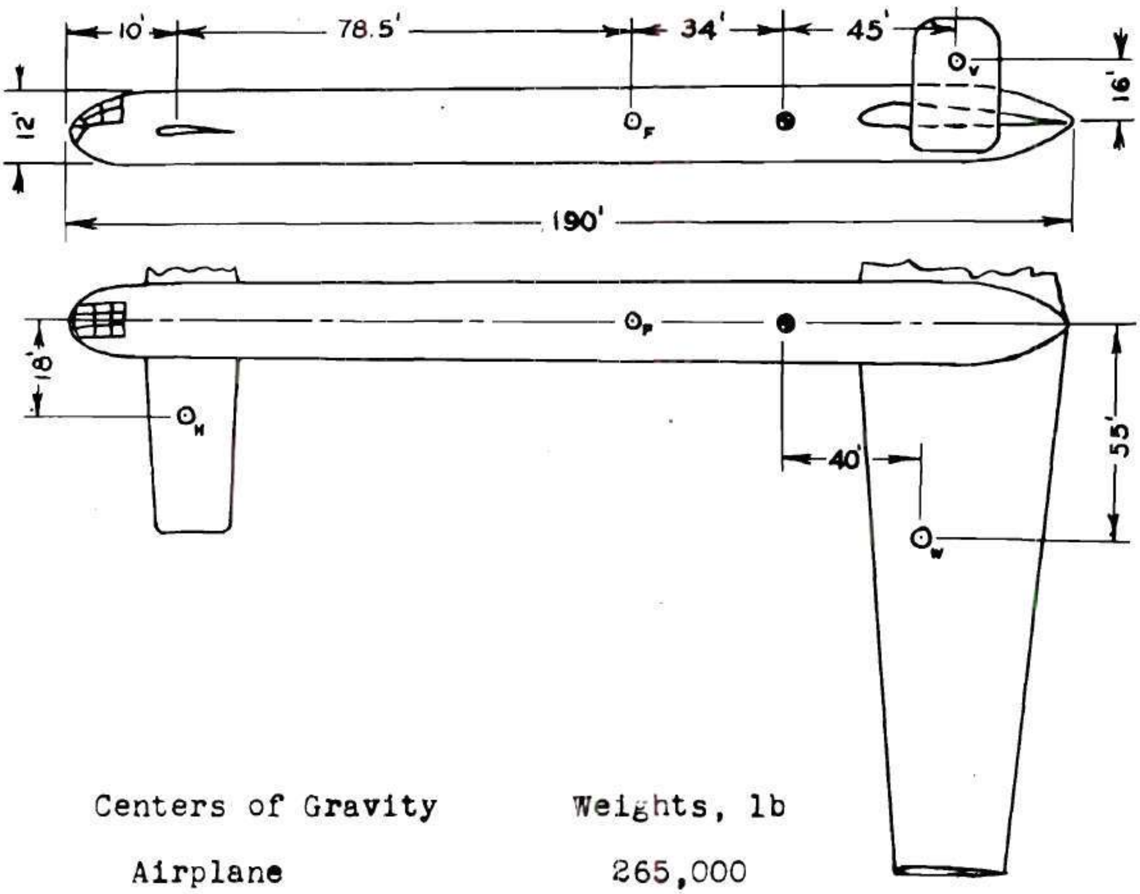
Specifications of the Model

b	12 in.	b	5.11 in.
c	1.085 in.	c	0.522 in.
S	13 in.	S	2.67 in.
W	0.75 oz.	S	1.904 in.
V	41.9 fps		

Table 4

Specifications of the XC-99

b	230.0 ft.	S	4772 sq. ft.
length. .	182.5 ft.	S	978 sq. ft.
height. .	57.5 ft.	S	542 sq. ft.
W	265,000 lb.		



Centers of Gravity	Weights, lb
Airplane	265,000
Forward plane panel	6,500
Fuselage	117,500
Wing panel	59,750
Vert. tail group	15,000

Fig. 1. The Hypothetical Canard

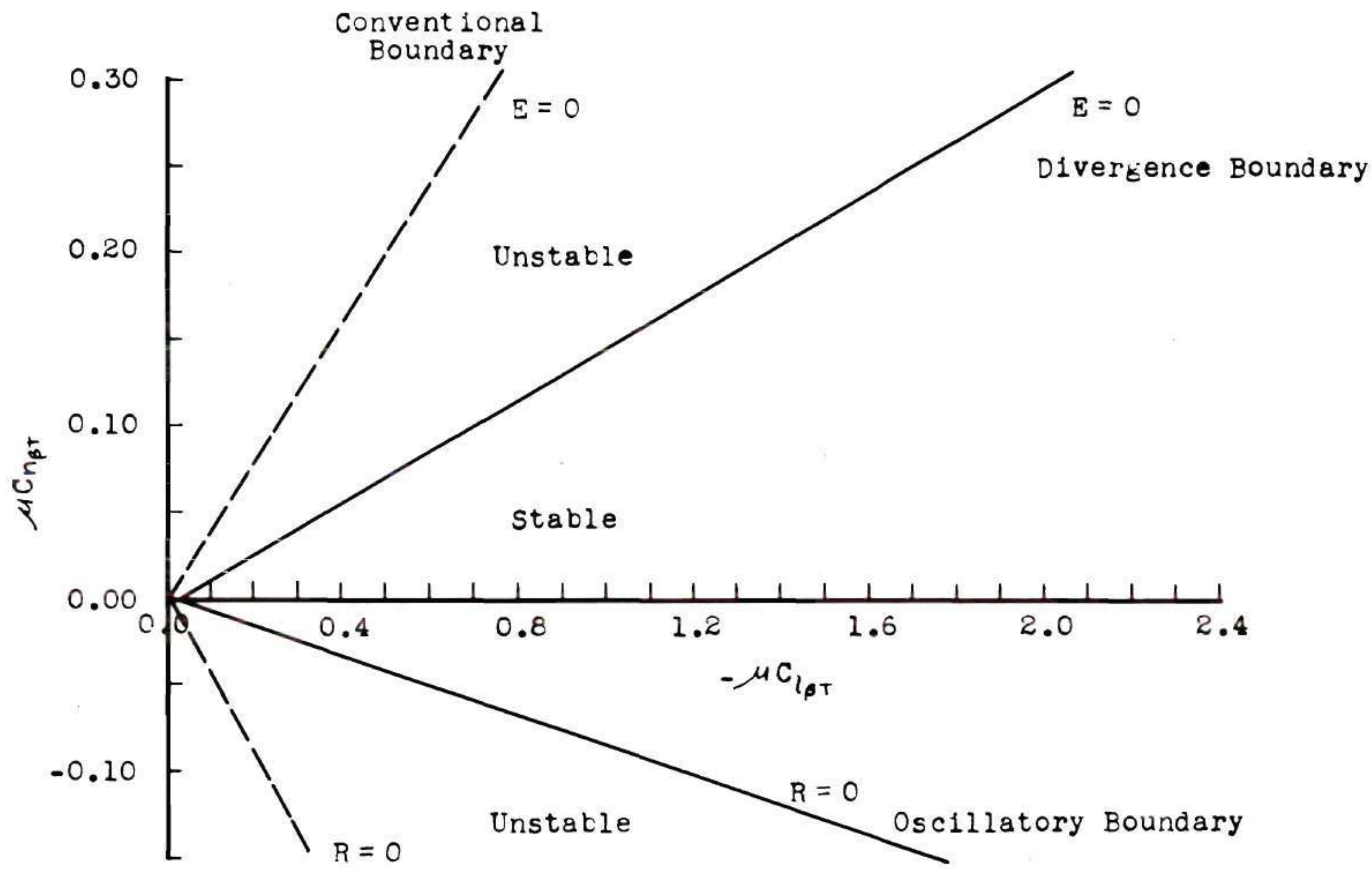


Fig. 2. Stability Boundaries for the Hypothetical Canard

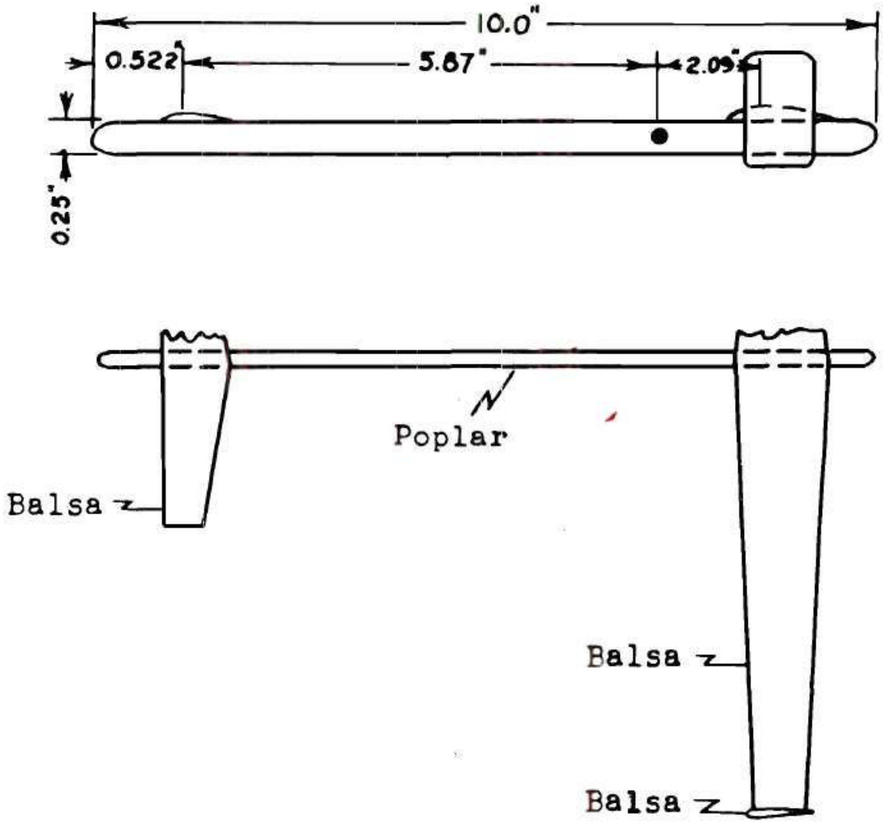


Fig. 3. The Model

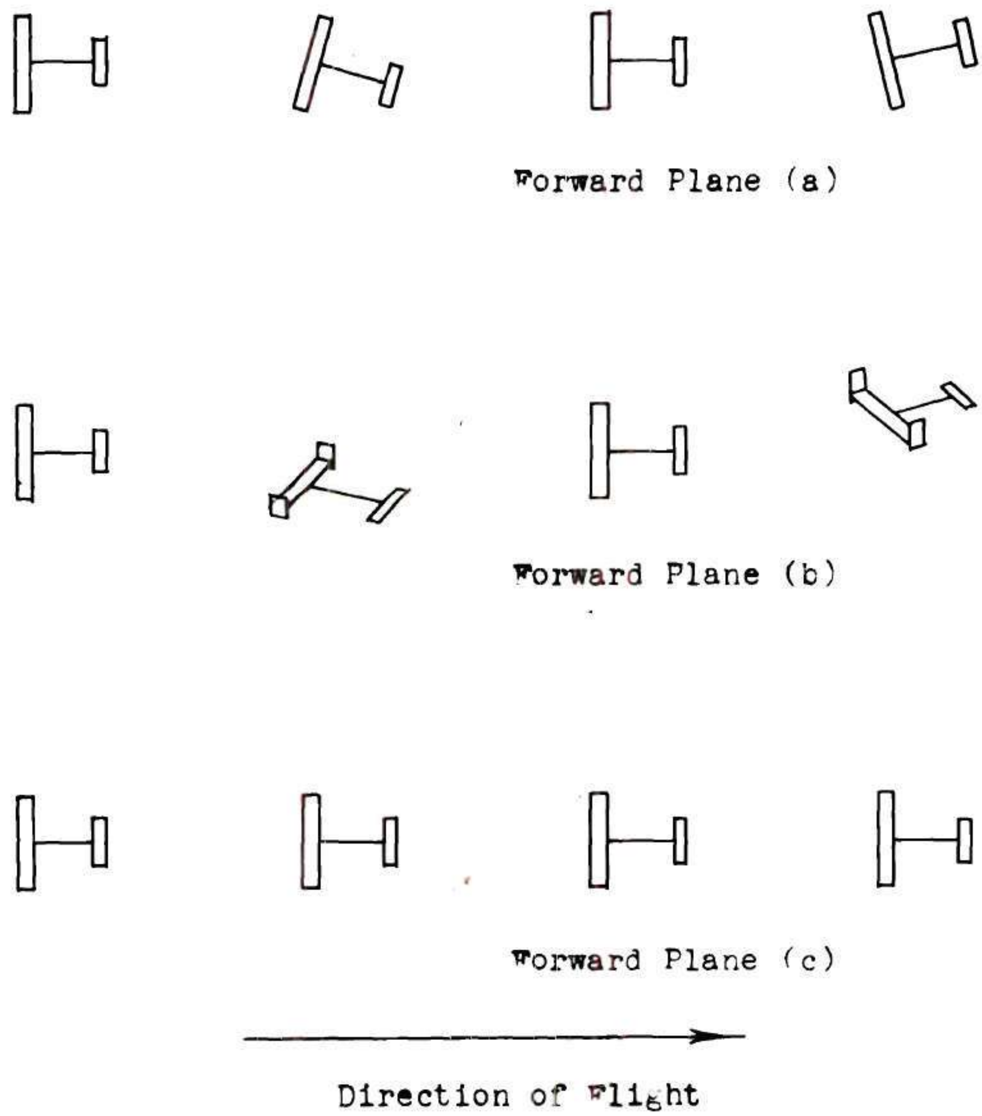


Fig. 4. Flight Paths of the Model (as viewed from above)

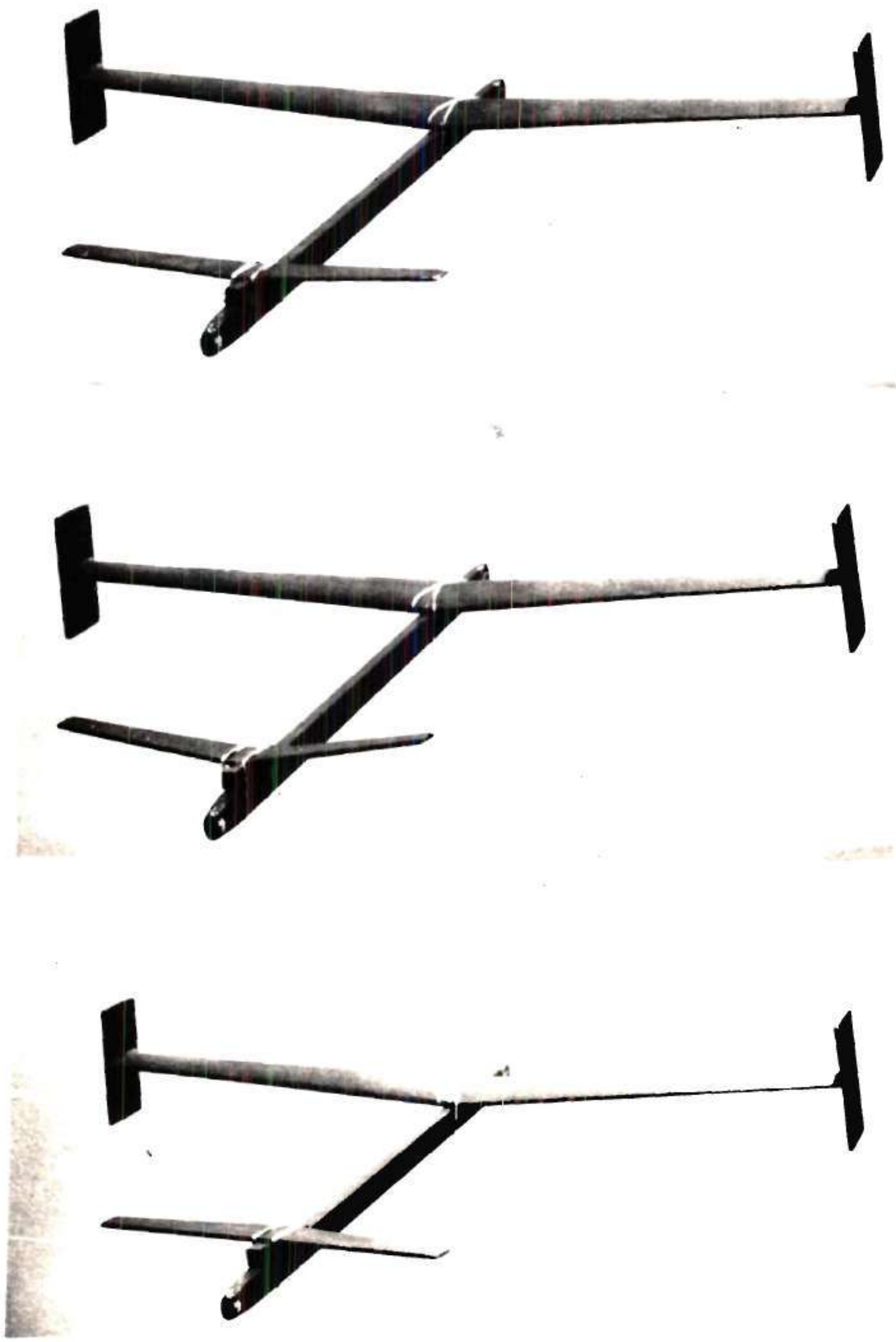


Figure 5. Photographs of the Model.

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