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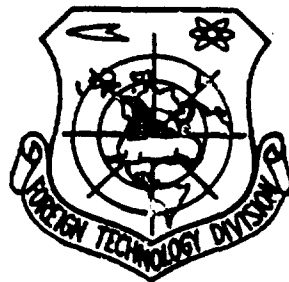
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CHARACTERISTICS OF DOUBLE-CANARD AERODYNAMIC SHAPE CONFIGURATION

by

Wang Bao-xing



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CHARACTERISTICS OF DOUBLE-CANARD AERODYNAMIC SHAPE CONFIGURATION

Wang Bao-xing
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The double-canard aerodynamic configuration is a new configuration recently developed for air-to-air missiles. The short range dogfight air-to-air missile newly successfully developed by France Matra R550, employs such an aerodynamic configuration.

Starting from the basic mechanism of mutual interference between the foreplane and the canard wing, this paper designed the profile of the canard wing in anticipation of obtaining larger lift effect. Experimental data from wind tunnel tests verified that a relatively large increase in the lift of the canard wing is obtained because of the presence of the foreplane. In addition, more importantly it also revealed a characteristic of this type of aerodynamic configuration--the pitch moment of the entire missile at small angles of attack shows a favorable nonlinearity. This paper analyzes the advantages of such "nonlinearity" in comparative detail. It is believed that it far exceeds the canard configuration and it is an ideal configuration for dogfight type of air-to-air missiles.

Figure 1 gives the profiles of the dynamometric models used in the tests of the double-canard and canard aerodynamic configurations. It also designated the lift surface in a unified manner.

I. DESIGN OF THE CANARD WING SHAPE AND THE LIFT EFFECT

By comparing the two aerodynamic configurations shown in Figure 1, it is not difficult to see that the double canard aerodynamic configuration is formed by the canard type configuration by installing a foreplane in front of the canard wing. The distance between the foreplane and the canard wing is very short. The mechanism of its mutual interaction is the same as the short spacing, small aspect ratio canard type configuration [1,2] which has been widely studied in recent years.

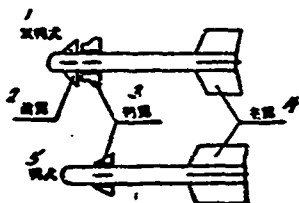


Figure 1. Designation of airfoil nomenclature.

1--double canard type;
2--foreplane; 3--canard wing;
4--main wing; 5--canard type

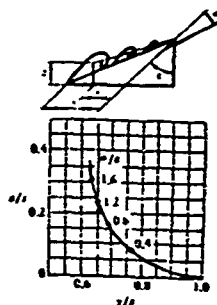


Figure 2. Correlation between the front fringe vortex nucleus position of triangular wing with attack angle

Previous studies discovered that for a large sweep-back triangular wing, when the attack angle is very small, the flow separates at the leading edge. Immediately afterward, a high revolution speed leading edge vortex is established to replace separation disturbance. When the leading edge sweep-back angle is sufficiently large, the vortex is very stable. Furthermore, over a wide attack angle range, the vortex lengthens with increasing attack angle. The nucleus of the vortex extends towards the inner upper direction of the wing surface. Figure 2 (quoted from [1]) gives the correlations between the vortex nucleus position and the attack angle α , as well as the half vortex angle ϵ of the wing surface. At a far away distance, the vortex nucleus explodes, which is called a "funnel" in engineering. Along with increasing attack angle, the "funnel" shifts forward. At a critical α value, it is shifted to the rear edge of the wing surface. Experiments proved that when the vortex nucleus is extended into the pressure rise region, it is easy to form the "funnel". When it extends into the pressure reducing region, formation of the "funnel" would be delayed.

In the vortex nucleus, due to the fact that the gas flow revolves at high speed and the pressure is low, where the vortex nucleus is on

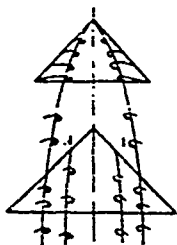


Figure 3. Interaction of the front vortices of two wing surfaces which are relatively closely spaced.

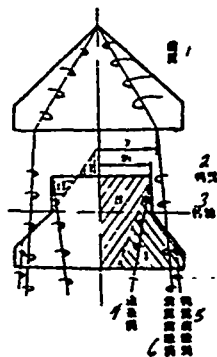


Figure 4. Schematic diagram of vortex series on the foreplane and canard wing
1--foreplane; 2--canard wing;
3--axis of rotation; 4--boundary vortex; 5--foreplane leading edge vortex; 6--canard leading edge vortex

the wing surface, a vortex nucleus suction effect is produced. When the vortex nucleus explodes on the wing surface to form the "funnel", the original neatly arranged flow structure

is changed into an irregular distribution if spinning. The pressure increases and subsequently the lift on the wing surface is reduced.

Two closely distanced wing planes (such as the foreplane and canard wing of the double canard type aerodynamic configuration) will mutually produce interference. The interference effect can be separated into two types depending on their relative position: In one, the front fringe vortex dragged from the foreplane surface passes above the rear wingsurface; i.e., it passes through the pressure reducing region of the rear wing surface. The vortex nucleus becomes even more stable. In addition, the velocity field induced by the leading edge vortex of the rear wing surface makes the leading edge vortex of the foreplane surface shift downward from the rear portion of the top surface of the rear wing surface. The vortex nucleus becomes even closer to the wing surface. Because the vortex nucleus suction effect produces added lift, under the action of the leading edge vortex of the foreplane, the central portion of the

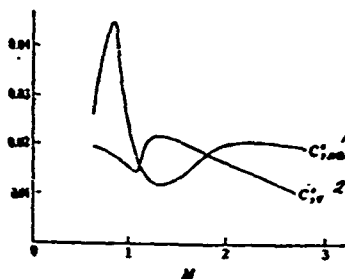


Figure 5. Experimental curve of C_y^{δ} double canard vs. C_y^{δ} canard

rear wing surface induces a very strong down wash while the wing tip part induces very intense up wash. The down wash in the middle is especially intense in the top end portion of the wing surface which will prevent the formation of front edge vortex. However, the up wash part will accelerate the formation of the leading edge vortex. As shown in Figure 3, due to the effect of the leading edge vortex of the foreplane, the leading edge vortex on the rear wing surface is not produced from the vertex but from point A. Moreover, it is even more intense than the one produced when it is isolated.

As for the rear wing surface, the down wash of the middle wing end portion must sacrifice some attack angle which is unfavorable. However, its leading edge vortex is intensified due to the coupling with the leading edge vortex of the foreplane. Furthermore, there are two vortex nuclei passing through its top surface and the vortex suction effect will produce very large added lift. The combined effect is very favorable. In the other version, the foreplane front edge vortex extends to the bottom surface of the rear wing, or extends into the pressure rise region. At this time, the vortex nucleus explosion to form the "funnel" region would be advanced. The "vortex suction effect" of the foreplane leading edge vortex will reduce the lift of the rear wing surface. This coupled effect is unfavorable; it should be avoided.

The mutual interaction between the foreplane and the canard wing of the double canard aerodynamic configuration is to realize the first coupling condition described above. To require the foreplane leading edge vortex to pass through the top surface of the canard wing so that the lift of the canard wing can be improved, it is necessary to carefully design the canard wing shape. Figure 4 is a planar diagram of a foreplane and a canard wing used as the dynamic model of the double canard type aerodynamic configuration. In the following, this special case will be used to explain what considerations are made in the design and the distribution situation of the vortex series.

References [1] and [2] discussed the short spacing canard type configuration of an aircraft. The position of the foreplane is designed to be higher than that of the rear wing so that the first coupling condition can be realized. For a missile, it is not possible to simply use the height of the position. The missile can roll. Looking from a certain direction, the foreplane is higher than the canard. By rotating 180° , it is the reverse. The design shown in Figure 4 is to use the profile of the canard wing and the position of the rotational axis. The canard wing is the control surface which must be deflected. When deflecting by an angle δ the area behind the rotation axis will be lower than the foreplane. If the position of the vortex nucleus of the foreplane leading edge vortex is being dragged from the wing surface $Y > Y_1$ (referring to Figure 4), it is possible to ensure that the foreplane leading edge vortex passes through the top surface of the canard wing. Subsequently, the favorable coupling effect is produced. From Figure 2, we can see that Y , the foreplane half vertex angle ϵ and the attack angle α are correlated. Corresponding to $\alpha_{\max}$, if we want to ensure that, within all the attack angle range, the foreplane leading edge vortex can pass through from the top surface of the canard wing, we must make $Y_{\min} > Y$.

It has been pointed out before that the effect of foreplane leading edge vortex makes the area of the I part shown in Figure 4 suffer from very intense down wash. The lift created by this part is

relatively small. In the design, this portion of the area is eliminated and moved to part II. The part in front of the rotation axis forms a rectangle. The sideline of the rectangular part will produce a boundary vortex. Thus, there are three vortices on the canard wing surface: boundary vortex, foreplane leading edge vortex and canard wing leading edge vortex. They are mutually coupled and reinforcement is obtained. Because of the "vortex nucleus suction effect", the lift of the canard is made to have a larger increment than that of the canard wing of the canard type configuration. Table 1 lists the partial derivatives of the canard wing lift coefficient with respect to the attack angle obtained from the double canard dynamometric model (without the main wing) wind tunnel tests and the partial derivatives of the canard wing lift coefficient with respect to attack angle of the canard type configuration (the same missile body, same canard wing, without main wing). The values are all arranged according to $\alpha = \pm 2^\circ$ range. The rudder deflection angle is $\delta = 20^\circ$, i.e., $\alpha + \delta = 20^\circ \neq 2^\circ$. The data in the table indicates that when the attack angle is large ($\alpha + \delta$ is the attack angle of the canard wing), the canard wing boundary vortex, foreplane front edge vortex and the canard front edge vortex are all intensified. The lift improvement effect is very significant.

TABLE 1

M	0.60	0.70	0.80	0.90	1.00	1.10
$C_{L\alpha}$	0.0408	0.0265	0.0274	0.0265	0.0313	0.0513
$C_{L\delta}$	0.0462	0.0495	0.0557	0.0479	0.0544	0.0696

Figure 5 gives the partial derivatives of the total missile lift coefficients obtained from the double canard type and canard type dynamometric model wind tunnel tests with respect to the rudder deflection angle δ . C_y^δ is approximately equivalent to the partial derivative of the canard wing lift coefficient with respect to the attack angle. In order to facilitate the comparison, the reference area of C_y^δ is chosen to be the canard wing area (the cantilever segment). The curve in Figure 5 shows that when $0.6 M < 1.0$ and $M > 1.8$,

$C_{y\text{double canard}}^{\delta} \gg C_{y\text{canard}}^{\delta}$. This further verifies the canard lift improvement effect of the double canard type aerodynamic configuration shown in Figure 4.

II. THE "NONLINEAR" EFFECT OF THE DOUBLE CANARD TYPE AERODYNAMIC CONFIGURATION

If we say that a foreplane added in front of the canard wing of the canard type aerodynamic configuration to improve the canard wing lift is the expected result of the double canard type aerodynamic configuration, then the results of wind tunnel tests revealed another important unexpected characteristic--the pitch moment M_z shows a favorable nonlinearity at small attack angles. Figure 6 shows the typical $M_z - \alpha$ wind tunnel test curve of the double canard type aerodynamic profile dynamometric model. On the curve at small attack angles (AA' and LL' segments), M_z increases with increasing attack angle ($M_z^{\alpha} > 0$). Only when going beyond point A' (or point L'), M_z then decreases with increasing attack angle α ($M_z^{\alpha} < 0$). This "nonlinearity" has the following advantages (referring to Figure 6).

(1) under the same static stability, it is possible to obtain a larger equilibrium attack angle as compared to the canard type aerodynamic configuration so that a larger transverse overload can be attained. Point A is the pitch moment generated by the 18° deflection of the canard wing ($\delta = 0^\circ$). The equilibrium point ($M_z = 0$) of the double canard type aerodynamic configuration is B,

$\alpha_{\text{double canard equilibrium}} = 16^\circ$. For the canard type configuration, the initial M_z ($\delta = 18^\circ$, $\alpha = 0^\circ$) and the M_z^{α} near the equilibrium point are the same as those of the double canard type configuration because its $M_z - \alpha$ curve is linear. The equilibrium point is B'. From Figure 6, we obtain $\alpha_{\text{equilibrium canard}} = 12^\circ$. Therefore,
 $\Delta\alpha = \alpha_{\text{equilibrium double canard}} - \alpha_{\text{equilibrium canard}} = 4^\circ$

This also means that when $M = 0.9$ and the canard wing deflects by 18° , the same pitch moment is created. Under the same static stability condition (identical M_z^{α}), due to the nonlinearity of the $M_z - \alpha$ curve of the double canard type also dynamic configuration,

an additional 4° of equilibrium attack angle is produced as compared to the canard type configuration, which corresponds to an increase in transverse overload by $1/4$.

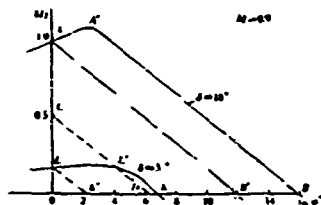
If the areas of the canard wings are identical, considering that the canard wing of the double canard type aerodynamic configuration is high (from Figure 5 we find that when $M = 0.9$, $C_y^{\delta \text{ doublecanard}} = 2 C_y^{\delta \text{ canard}}$) for the same deflection of 18° , then

$$M_{Z \text{ canard}} (\alpha = 0, \delta = 18^\circ) = \frac{1}{2} M_{Z \text{ double canard}} (\alpha = 0, \delta = 18^\circ)$$

The starting point of the canard type configuration is at C. If the same M_Z^a is to be maintained at the equilibrium point, then the equilibrium point is at D, $\alpha_{\text{equilibrium.canard}} = 6^\circ$.

$$\Delta \alpha = \alpha_{\text{equilibrium.double canard}} - \alpha_{\text{equilibrium.canard}} = 10^\circ$$

Figure 6. The pitch moment curve of the double canard type aerodynamic configuration



The maximum useable overload is

$$n_{\text{max}} = (C_y^{\alpha} \cdot \alpha_{\text{equilibrium}} + C_y^{\delta} \delta_{\text{max}}) \frac{q \cdot s}{w}$$

where C_y^{α} - partial derivative of the lift coefficient of the missile with respect to the attack angle α ;

C_y^{δ} - partial derivative of the lift coefficient of the missile with respect to the rudder deflection angle δ ;

δ_{max} - maximum rudder deflection angle;

$\alpha_{\text{equilibrium}}$ - equilibrium attack angle at maximum rudder deflection angle;

q - dynamic pressure; s - reference area, w - missile weight

By taking into account that $C_y^{\alpha} \cdot \alpha_{\text{equilibrium}} \gg C_y^{\delta} \cdot \delta_{\text{max}}$, we can consider in approximation that the maximum useable overload is proportional to the maximal equilibrium attack angle. This also

means that when the canard wing area is identical and the deflection is the same 18° , under the condition that the same static stability is to be maintained, the equilibrium attack angle of the double canard type aerodynamic configuration is larger by 10° than the equilibrium attack angle of the canard type aerodynamic configuration. The transverse useable overload increases approximately 1.6 times.

(II) The dynamic response speed is improved as compared to the canard type configuration. When the canard wing is deflected by 3° , a pitch moment M_z is produced ($\alpha = 0$, $\delta = 3^\circ$) which is the point L in Figure 6. As the attack angle starts to increase, finally it reaches the static equilibrium point K. The double canard type aerodynamic configuration varies from the solid line LL' to point K. In the segment LL', with increasing α , M_z also increases. Consequently, the rate of the attack angle increase is also increased. Beyond point L', with increasing attack angle, M_z decreases. The value of M_z^α at point K is negative; therefore, K is a static stability point. If it is the canard type configuration, the M_z^α at the equilibrium point is identical; then it varies from point L to point K' along a straight line. Thus, as α increases, M_z would decrease linearly and the rate of attack angle increase would also decrease. From these results, we can see that the dynamic response speed of the double canard type aerodynamic configuration is much faster than that of the canard type aerodynamic configuration.

This nonlinearity is produced due to the addition of the foreplane. Figure 7 lists the forces exerted on various parts of the double canard type missile. From the diagram we obtain

$$M_z = Y_{\text{head}} X_1 \sin \alpha + Y_{\text{foreplane}} X_2 \sin \alpha + Y_{\text{canard}} X_3 \sin (\alpha - \epsilon_1) - Y_{\text{main wing}} X_4 \sin (\alpha - \epsilon_2)$$

where Y_{head} - lift of the head; $Y_{\text{foreplane}}$ - lift of the foreplane; Y_{canard} - lift of the canard wing; X_1 - distance between Y_{head} and the center of gravity; X_2 - distance between $Y_{\text{foreplane}}$ and the center of gravity; X_3 - distance between Y_{canard} and the center of gravity; X_4 - distance between $Y_{\text{main wing}}$ and the center of gravity; ϵ_1 - the average down-wash angle at the canard wing; ϵ_2 - the average down wash angle at the main wing.

When α is relatively small, $\sin \alpha = \alpha$. The above equation can be rewritten as

$$M_z = [C_y^{\alpha} \text{ head } S_{\text{head}} X_1 \alpha^2 + C_y^{\alpha} \text{ foreplane } \delta \text{ foreplane } X_2 \alpha^2 + C_y^{\alpha} \text{ canard } S_{\text{canard}} X_3 (\alpha - \epsilon_1) (\alpha + \delta - \epsilon_1) - C_y^{\alpha} \text{ main wing } S_{\text{main wing}} X_4 (\alpha - \epsilon_2)] q$$

Under the condition that $\delta = \text{const}$ and $(S_{\text{foreplane}} + S_{\text{canard}})$ is not much smaller than $S_{\text{main wing}}$ (such as in the double canard type aerodynamic configuration dynamometric model $S_{\text{foreplane}} + S_{\text{canard}} = 0.8 S_{\text{main wing}}$ shown in Figure 1), $(\alpha + \delta/2 - \epsilon_1) \gg (\alpha - \epsilon_2)$ in the vicinity of small α , then $M_z^{\alpha} > 0$. When α is relatively large, $(\alpha + \delta/2 - \epsilon_1)$ and $(\alpha - \epsilon_2)$ are not too different in magnitude, $S_{\text{main wing}} X_4$ is relatively large. Therefore, the last term in the above formula has the major effect. Hence, $M_z^{\alpha} < 0$, which is the cause of non-linearity. In the canard type aerodynamic configuration, due to the fact that the canard wing area is small, the main wing lift always has the major effect. Therefore, M_z^{α} is always less than zero.



Figure 7. Schematic diagram of forces exerted on various parts of a double canard type missile
1--Y head; 2--Y foreplane;
3--Y canard; 4--Y main wing

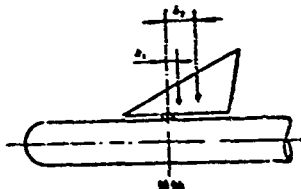


Figure 8. Hinge moment of the canard type control
1--rotation axis

III. CONTROL CHARACTERISTICS OF THE DOUBLE CANARD TYPE AERODYNAMIC CONFIGURATION

It has been pointed out previously that with regard to the canard wing of a double canard type configuration, if the shape and the rotation axis position are designed properly, the efficiency of the

canard wing (C_y^δ) can be improved. Another requirement as a control surface is that hopefully the hinge moment is small. Thus, it is possible to have a service mechanism which is not too large and heavy in order to satisfy the required characteristics in one meantime. It is commonly known that the key to reducing the hinge moment is to reduce the variation of the pressure center of the canard wing under various conditions. For example, as in canard type control, the canard wing is triangular (as shown in Figure 8) and the pressure center in a subsonic flow is located at between 0.3-0.4 average aerodynamic chord. In supersonic flows, it is close to 0.5 average aerodynamic chord. The control stability requires that the rotation axis of the canard wing ought to be located in front of the pressure center. The maximum hinge moment is (see Figure 8).

$$M_{\text{hinge}} = -ph_2 = -ph_1 - P(h_2 - h_1)$$

where: M_{hinge} - maximum hinge moment; P - maximum perpendicular force component on the surface of the canard wing; h_1 - minimum distance between the subsonic pressure center and the rotation axis; h_2 - maximum distance between the supersonic pressure center and the rotation axis.

If the maximum pressure center displacement $h_2 - h_1$ is very small, as long as h_1 is designed to be sufficiently small, it is possible to reduce the hinge moment. The pressure center displacement of canard type control is about 0.2 average aerodynamic chord length. Therefore, it is difficult to make the hinge moment very small.

The variation of the pressure center position of the double canard type aerodynamic configuration with velocity is not too large. Qualitatively, we can explain in this way that in zone A of the canard wing (referring to Figure 4) the top surface is under the influence of the foreplane front edge vortex, canard wind boundary vortex and canard wing front edge vortex. The suction effect of the vortex nucleus makes the lift increase in this region. In addition, it is located in the upwash region of the incoming flow, and the attack angle also increases. Therefore, zone A has a large contribution to the lift of the entire canard wing. Zone B does not have

vortex suction and is situated in the downwash zone of incoming flow. It has very small contribution to the canard wing lift. The combined effect of zones A and B makes the subsonic pressure center to approach 0.5 average aerodynamic chord length. For supersonic flow, it is even closer to 0.5 average aerodynamic chord length. This indicates that the variation of pressure center of the canard wing in the double canard type aerodynamic configuration with the Mach number is very small. Its pressure center position is very difficult to obtain accurately by calculation. It must be determined with the assistance of wind tunnel tests. With regard to the canard wing profile shown in Figure 4, if it is designed properly, the variation of the pressure center position X is

$$0.45b_{AK} < X < 0.5b_{AK}$$

30

where X is the distance from the starting point of the average aerodynamic chord to the pressure center, and b_{AK} is the average aerodynamic chord length of the cantilever segment. The maximum variation of the pressure center with velocity is $h_2 - h_1 = 0.05 b_{AK}$, which is 1/4 of that of the canard type aerodynamic configuration. If the rotation axis is designed to be in the $0.43 b_{AK}$ position, then

$$M_{\text{hinge}} \cdot \text{double canard} = 0.07 pb_{AK}$$

$$M_{\text{hinge}} \cdot \text{canard} = 0.22 Pb_{AK}$$

Under the condition of identical aerodynamic force P , the hinge moment of the double canard type configuration is only 1/3 that of the canard type configuration.

Summarizing the above description, the double canard type configuration can attain higher maneuverability and faster dynamic response speed than the canard type configuration, while the required rudder power is less. Therefore, it is an ideal configuration for a dogfight type air-to-air missile. The low altitude ground-to-air missile with high maneuverability requirements can also adopt this configuration.

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