

A study of the influence of the front and rear wing interference on the lift characteristics of the 'diamond-back' wing kit

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Abstract. The 'diamond-back' wing kit is connected by hinges with the front and rear wings, which can be folded and expanded. As folded, it can be attached to the surface of the missile body. The 'diamond-back' wing kit will have good prospects for application in future embedded weapon systems under conditions of critical weapon size requirements. Unlike the traditional single swept-back wing layout, the diamondback wing has significant aerodynamic interferences due to the close position of the front and rear wings; recognition and rational use of the aerodynamic interference between the two sets of wings is of great significance in the shape design of similar "diamondback" wings. This paper carries out a study of the lift characteristics of the diamondback wing by numerical simulation, and analyses the variation of the lift characteristics of the front and rear wing components with Mach number due to the interference between the front and rear wings. In particular, the effect on the nonlinear characteristics of the slope of the lift line versus Mach number in the transonic range due to the generation of shock waves on the upper and lower wing surfaces is investigated. The results of the study show that the influence of the front wing on the rear wing is mainly reflected in the downwash effect, and the slope of the lift curve of the rear wing layout is significantly reduced compared with the case without front wing interference. The interference of the rear wing with the front wing causes the suction peak on the upper surface of the front wing to increase, and as the Mach number increases, the damping effect of the rear wing causes the acceleration of the fluid on the upper and lower wing surfaces of the front wing to flatten out compared to the layout of the front wing alone. Overall, the "diamond-back" wing can improve the nonlinearity of the lift characteristics of the wing-body combination with the variation of Mach number to a certain degree through the combination of the front wing and the rear wing, and the mutual interference of the two sets of wings in aerodynamic aspect.

Keywords: "diamond back"; guided missile; front wing; rear wing; lift curve slope.

1. Introduction

The "diamondback" also known as "diamondback" wing kit is a kind of combined wing that connects the front and rear wing strips through hinges in the form of a truss and can be folded and unfolded, and the front and rear wings are folded and affixed to the surface of the body of the missile before launch, and can be quickly unfolded after launch to serve as a lift component of the missile. One of the major advantages of this structure is that it takes up less space, which can increase the missile carrying capacity of a single aircraft[1]. In addition, the aerodynamic performance of the "diamondback" wing is better, with higher lift-to-drag ratio and lighter mass, which is conducive to gliding range extension and out-of-defense area launch.

A comparison of the Small Diameter Bomb and the Joint Standoff Weapon demonstrates that the Small Diameter Bomb is low cost, small in size, low in collateral damage, and can significantly increase the payload of a single aircraft.

The United States has successfully applied "diamondback" wings to both the extended-range Joint Direct Attack Munition (JDAM) and the Small Diameter Bomb [2,3] (code name GBU-39). Based on the retracted wing configuration of the GBU-39, Lt. Judson et al. [4] conducted numerical simulations of aerodynamic characteristics and compared them with experimental results. The results

of flight experiments of GBU-39 dropped from a embedded missile bay of an F22 fighter are reported in the literature [5,6].

Due to the formation and development of shock waves on the upper and lower wing surfaces, the traditional single-swept-wing layout will make the variation of the slope of the lift curve of the missile appear to be large nonlinearity in the transonic stage versus Mach number[7,8], which will affect the aerodynamic performance of the missile, and bring certain difficulties on the flight control, especially. However, the "diamondback" wing consists of two groups of wings, the front wing and the rear wing, and there is a large interference between the two groups of wings. If the interference between the two groups of wings can be reasonably utilised to reduce the nonlinearity of variation of the slope of the curve of lift in the trans-sonic range caused by the influence of shock waves versus Mach number, the aerodynamic performance of the whole missile can be improved. Based on this, this paper investigates the aerodynamic characteristics of a typical "diamondback" wing-body assembly by using numerical simulation, compares the aerodynamic performance with that of separate a front wing and a separate rear wing, and the effect of the interference between the front and rear wings of the "diamondback" wing on the aerodynamic performance is analysed, which has some guiding significance on how to improve the aerodynamic performance of similar "diamondback" wings in terms of shape design.

2. Geometric shape

The basic shape parameters of the studied "diamondback" wing-body assembly are shown in Figure1 (a), the diameter of the body is d , the length of the body is $10.7d$, the front wing is a rectangular wing with chord length of $0.57d$, swept back angle of 30° , and spread length of $7.7d$.

In order to compare the aerodynamic performance of the "diamondback" wing (Base) with that of the separate front wing (Body-FW) and separate rear wing (Body-BW), and to analyse the interference of the front and rear wings of the "diamondback" wing, the rear and front wing components of the "diamondback" wing are removed separately to obtain the combined body layout of the separate front and separate rear wings shown in Fig. 1(b) and Fig. 1(c).

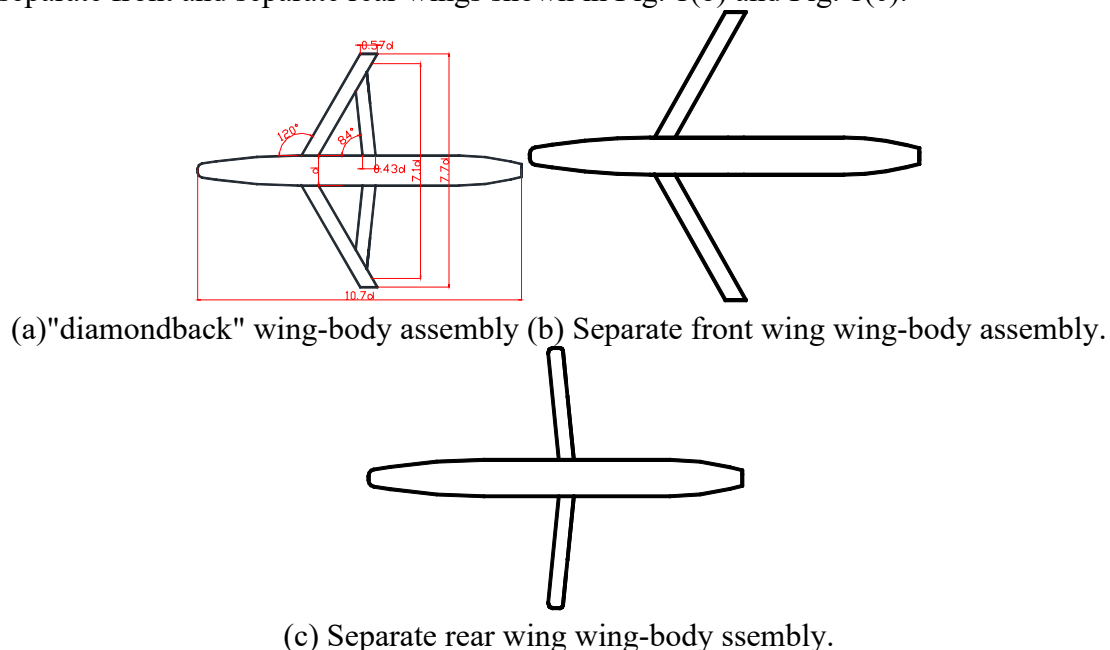


Figure 1. Basic geometry parameters of the mode.

3. Numerical methods and meshing

The governing equations adopt the Reynolds-averaged N-S equations, the finite volume method is used for spatial discretization, the spatial inviscid fluxes are discretized using the ROE format, the

viscous fluxes are discretized using the second-order center-difference format, and the time term is solved by the implicit LU-SGS method. In order to speed up the convergence speed, local time step and multi-mesh techniques are employed. The turbulence model is a two-equation $k-\omega$ SST model.

In this paper, the computational grid adopts the idea of "three-level" mesh generation, that is, the first level near the object surface mainly simulates the viscous surface layer, the second level in the middle mainly simulates the vortex of space, and the third level near the far field mainly satisfies the far-field boundary conditions. The computing grid adopts multiple docking structure meshes; the space and object surface are both "H" shaped meshes. The mesh of the first layer of the attached surface layer is $y^+=1$, and the change rate is about 1.2. The amount of full-missile half-mode grids is 4.3 million. The surface mesh and spatial topology of the computed model are shown in Figure 2.

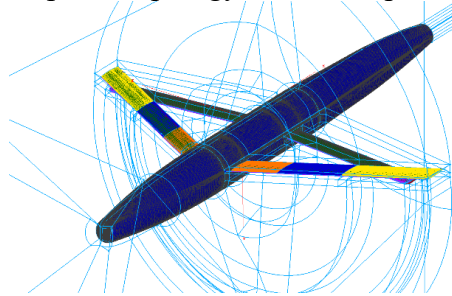


Figure 2. Mesh topology of the model.

4. Results and analyses

4.1 Lift characteristics of separate front wing layout

Figure 3 shows the variation curve of the lift curve slope with Mach number for the front wing-body assembly (Body-FW), it can be seen that this lift curve slope curve is consistent with the flow characteristics of a typical wing surface, and at low speeds due to the effect of compressibility, the slope of the lift curve gradually increases; as the Mach number increases, shock waves begin to appear on the upper surface of the wing. It can be seen from the pressure coefficient distribution of $z/l=0.45$ section plane shown in Figure 5 (Figure 4 is a schematic diagram of the typical locations along the span) and the distribution of the pressure contour in Figure 6 that at $M=0.8$, significant shock waves generate at 30% from the local chord toward the head, the pressure decreases after the shock wave and the slope of the lift curve further increases. From point a to point b in Figure 3, define the upward slope of the lift curve slope with Mach number as $(CL_{\text{increase}})_M$, at this point $(CL_{\text{increase}})_M=0.172$; as the Mach number increases further, the upper wing surface shock wave position shifts back and the intensity of the shock wave increases; when the Mach number reaches about 0.9, a supersonic zone also appears on the lower wing surface and expands rapidly, with the result that the lower wing surface pressure decreases and the slope of the lift curve decreases; From point c to point d in Figure 3, define the downward slope of the lift curve slope with Mach number as $(CL_{\text{decrease}})_M$, at this point $(CL_{\text{decrease}})_M=0.118$; when the Mach number reaches near 0.95, the supersonic zone on the lower wing surface no longer expands, but the supersonic zone on the upper wing surface continues to expand, so the slope of the lift curve shows an upward trend again. Define the Mach number range spanned between the two peak points b and d of the lift curve slope in Fig. 3 as ΔM_{bd} , at which point $\Delta M_{bd}=0.15$; After the upper and lower wing surfaces are in supersonic flow, the slope of the lift curve decreases in proportion to the $1/\sqrt{M^2-1}$.

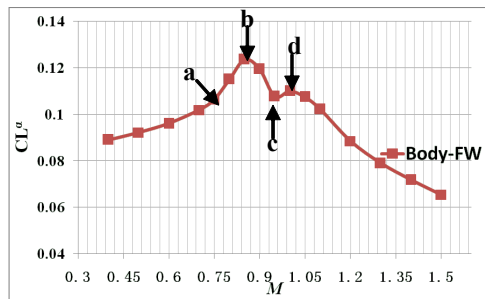


Figure 3. Lift curve slope versus Mach number of the model with forward wing.

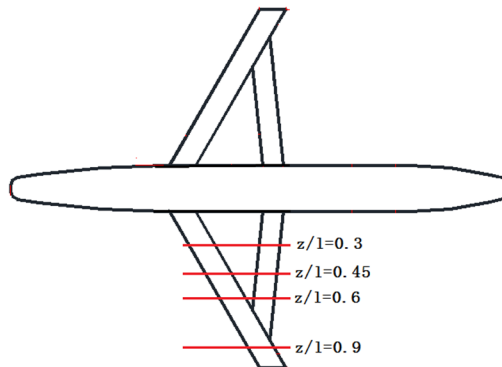


Figure 4. Typical locations along the span.

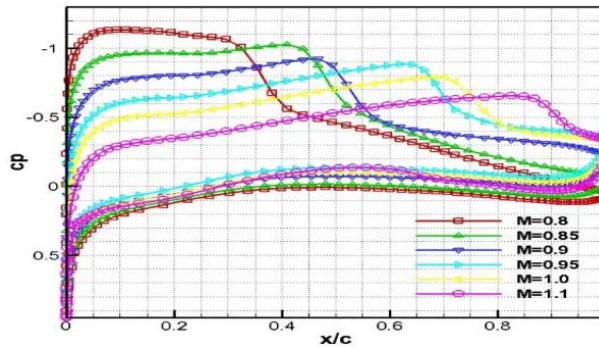


Figure 5. Pressure coefficient distribution of z/l=0.45 section plane.

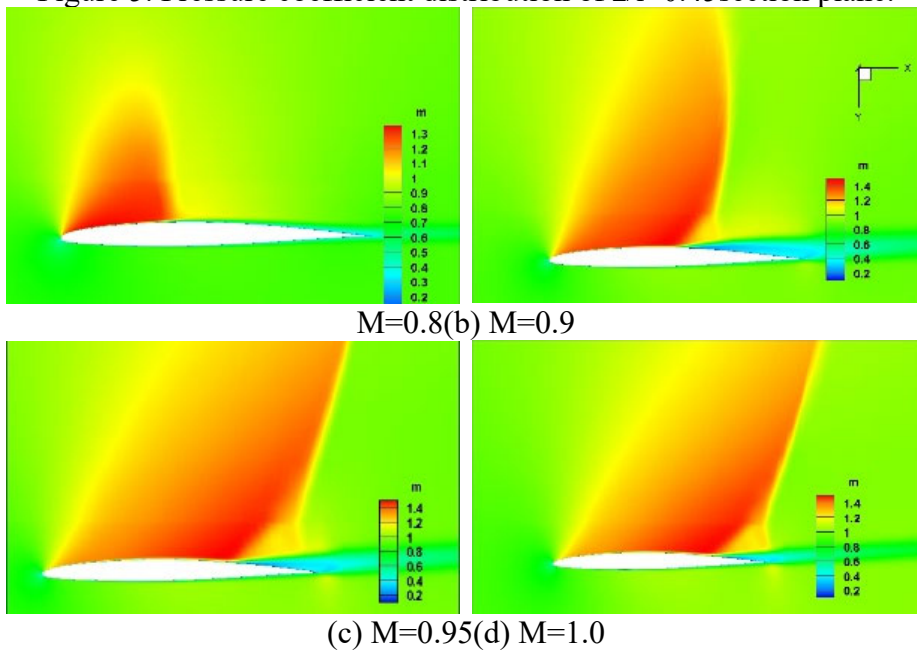


Figure 6. Mach number counter of z/l=0.45 section plane.

4.2 Lift characteristics of separate rear wing layout

The trend of the variation of the lift curve slope versus Mach number (shown in Fig. 7) for the rear wing-body assembly (Body-BW) is basically the same as that for the front wing-body assembly; Due to the forward swept layout of the rear wing and the forward swept angle is only 6° , the supersonic region starts to appear on the upper wing surface at around $M=0.8$ (as shown in the pressure coefficient distribution of $z/l=0.45$ section plane at the typical Mach number shown in Fig. 8), which is slightly earlier than that of the lower wing surface of the forward wing-body assembly which appears supersonic region only at around 0.9, and the trough point of the lift curve slope emerges at Mach 0.85 or so, which is about 0.1 ahead of the front wing-body assembly. And $(CL_{increase})_M = 0.0922$, $(CL_{decrease})_M = -0.209$, $\Delta M_{bd} = 0.2$

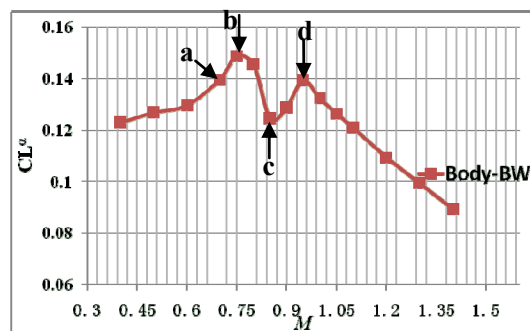


Figure 7. Lift curve slope versus Mach number of the model with backward wing.

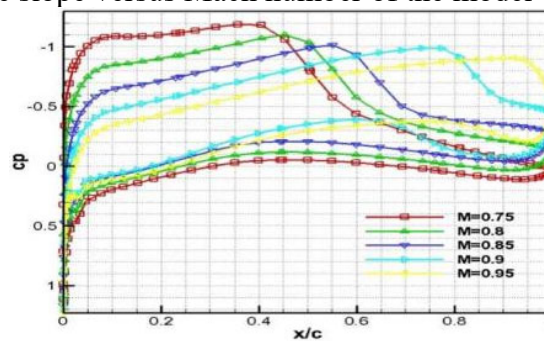


Figure 8. Pressure coefficient distribution of $z/l=0.45$ section plane.

4.3 "Diamondback" wing lift characteristics and front and rear wing interference

The "diamondback" wing is formed by the combination of the front wing and the rear wing, and its aerodynamic characteristics are the result of the front wing and the rear wing, as well as the mutual interference of the front wing and the rear wing. From the variation curve of the slope of the lift curve versus the Mach number (Fig. 9), it can be seen that its pattern is basically the same as that of the separate front and rear wing-body assembly; Mach number corresponding to the peaks and troughs of the slope of the lift curve is between the characteristics of a separate front wing and a rear wing-body assembly; and from the measurements of $(CL_{increase})_M = 0.118$ and $(CL_{decrease})_M = -0.0097$ of the "diamondback" combination, it has larger reduction compared to separate front wing-body assembly ($(CL_{increase})_M = 0.172$, $(CL_{decrease})_M = -0.118$); that is, the slope of the lift curve varies more gently with Mach number in both the ascending and descending segments, which is beneficial to the performance of the vehicle. In particular, ΔM_{bd} is only 0.1, which is also a significant reduction compared to the separate front wing-body assembly ($\Delta M_{bd} = 0.15$) and the separate rear wing-body assembly ($\Delta M_{bd} = 0.2$). It can be seen that the "diamondback" wing, through the combination of the front and rear wings can improve the nonlinearity of the lift characteristics of the wing-body combination with the change of Mach number to a certain degree as a result of the mutual interference of the two groups of wings in terms of aerodynamics, which is beneficial to the cruise characteristics and the design of the control system.

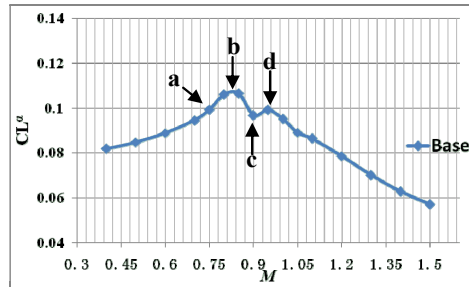


Figure 9. Lift curve slope versus Mach number of the model with “diamond wing”.

Figure 10 shows the variation of the front wing lift curve versus Mach number of the "diamondback" wing assembly layout and the variation of the front wing lift curve versus Mach number of the separate front wing assembly layout. From the figure, it can be seen that before $M=0.85$, i.e., before the first lift curve slope peak is generated, the lift curve slope of the front wing of the "diamond-back" wing assembly layout is slightly larger than that of the separate front wing layout. From the comparison of pressure coefficients of typical section with $M=0.8$ shown in Fig. 11, it can be seen that the interference of the rear wing will make the suction peak on the upper surface of the front wing increase, and make the shockwave position backward, and at the position of the front wing close to the winglet, the lower surface of the front wing and the upper surface of the rear wing form a flow channel, and there is an acceleration of the partial airflow in the channel, which makes the pressure of the lower wing surface reduce (as comparison shown in the comparison of pressure coefficients of the section with $z/l=0.9$ in Fig. 11), with a slight loss of lift. As the Mach number increases, as shown in Fig. 5, the shockwave position on the upper wing surface of the separate forewing-body assembly is rapidly shifted backward at $M=0.95$, and as the spreading position develops the shockwave position is farther away from the front edge of the wing but the shock position of the upper wing surface of the front wing of the "diamondback" assembly varies more gently with Mach number, and the shock position of the same spreading station is closer to the front edge than that of the separate front wing-body assembly. When the Mach number reaches 1.05, near the wing root position, the pressure coefficients of the upper and lower surfaces of the wing of the "diamondback" and separate front wing layout tend to be the same, while the closer to the winglet position, the distance between the front wing and the rear wing is gradually shortened, and the interference of the rear wing with the front wing is gradually strengthened, and at this time, almost all of the upper wing surfaces of the separate front wing are supersonic flow, and the supersonic zone on the upper surface of the "diamondback" forewing is still under development. The interference of the rear wing with the front wing is reflected in the change of the slope of the lift curve; the main effects of this are that a slight rearward shift of the trough of the lift curve slope of the rhombic dorsal front wing, the second wave peak tends to flatten out, and the slope of the lift curve tends to flatten out with the change of the Mach number.

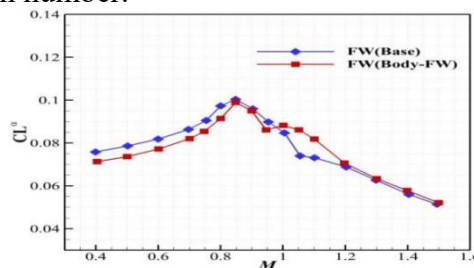


Figure 10. Forward wing lift curve slope versus Mach number.

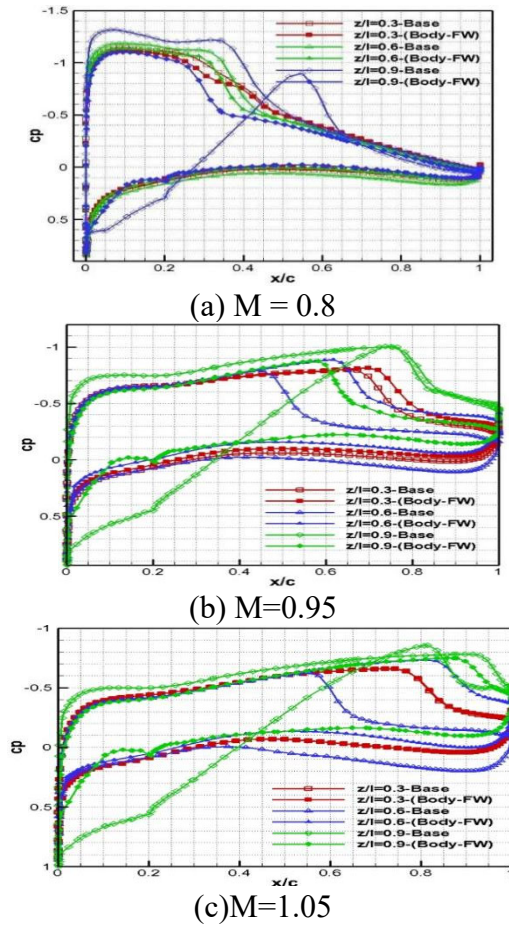


Figure 11. Pressure coefficient distribution of typical section planes of forward wings.

Figure 12 shows a comparison of the variations of the slope of the rear wing lift curves versus Mach number for the diamondback layout and the separate rear wing assembly. Figure 13 shows a comparison of the pressure distributions in typical section between the "diamondback" assembly and the separate rear wing layout for $M=0.85$. From the figure, it can be seen that compared with the layout of the separate rear wing, the loss of the lift curve slope of the "diamond-back" rear wing is larger, which is mainly due to the downwash of the front wing of the diamond-back on the airflow that makes the local angle of attraction of the rear wing lower, resulting in the reduction of the slope of the lift curve.

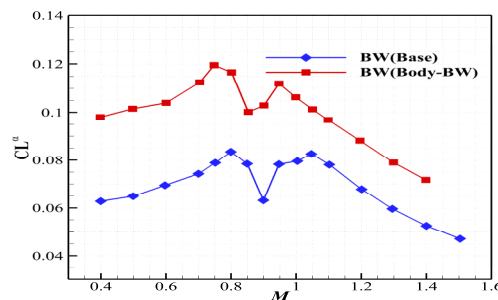


Figure 12. Forward wing lift curve slope versus Mach number.

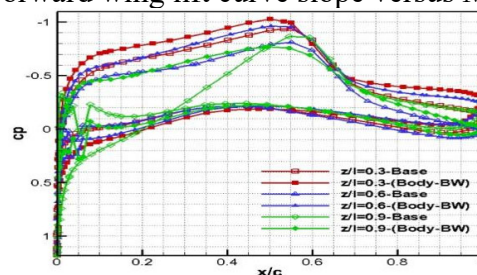


Figure 13. Pressure coefficient distribution of typical section planes of backward wings at $M=0.85$.

5. Conclusion

This paper carries out a study on the lift characteristics of the "diamondback" wing by means of numerical simulation, and the effect on the nonlinear characteristics of the slope of the lift line versus Mach number in the transonic range due to the generation of shock waves on the upper and lower wing surfaces is investigated. The following conclusions were obtained:

(1) The lift characteristics of both the single front wing and single rear wing layouts are in accordance with the characteristics of a large spin ratio wing-body assembly layout, i.e., in the transonic range, due to the generation and development of shock waves on the upper and lower wing surfaces, the change of the slope of the lift curve with the Mach number has a significant non-linearity. Specifically, as the Mach number increases, the upper wing surface begins to show shock waves, and the slope of the lift curve increases as the Mach number increases; as Mach number continues to increase, the generation of lower wing surface shock waves causes a rapid decrease in the slope of the lift curve; subsequently, the upper and lower wing surface shock waves moved backward at the same time, and the slope of the lift curve picked up a little; as Mach number of the incoming flow increases further, both the upper and lower wing shocks reach the trailing edge, and the slope of the lift curve begins to decrease again.

(2) On the interference between the front and rear wings, the influence of the front wing on the rear wing is mainly reflected in the downwash influence; the lift curve slope of the rear wing layout is significantly lower than in the case of no front wing interference. Interference of the rear wing with the front wing increases the suction peak on the upper surface of the front wing; As the Mach number increases, the damping effect of the rear wing smoothes the acceleration of the fluid in the upper and lower wing surfaces of the front wing compared to the front wing layout alone.

(3) Overall, the "diamond-back" wing can improve the nonlinearity of the lift characteristics of the wing-body combination with the Mach number to a certain degree through the combination of the front wing and the rear wing, and the mutual interference of the two sets of wings in aerodynamic aspect.

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