Numerical Study on Aerodynamic Characteristics of Variable-sweep Morphing Aircraft at Transonic Speeds

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Abstract. The variable-sweep morphing aircraft (VMA) has both high speed and low speed flight performance, and can be competent for combat tasks and practical requirements in different flight environments. Aerodynamic characteristics of VMA have a great impact on flight performance. The transonic stage is particularly important in the whole variation process. It is also one of the most difficult problems in aerodynamic layout design of aircraft. In order to explore the aerodynamic characteristics of the VMA at transonic speeds, this paper adopts an efficient engineering algorithm. The aerodynamic characteristics of VMA at different Sweepback Angle, Angle of attack, Mach number and Altitude are analysed. The result demonstrates that: Sweepback Angle has great influence on aerodynamic characteristics of aircraft. For the lift coefficient, at subsonic speeds, small sweep has great influence. When the Angle of attack (AOA) is 12°, the sweepback changes from 45° to 25°, and the lift coefficient increases by 48.9%. At transonic speeds, large sweepback has great influence. When the AOA is 12°, the sweepback changes from 75° to 55°, and the lift coefficient increases by 85.7%. For the drag coefficient, at subsonic speeds, small sweepback has great influence. When the AOA is 12°, the sweepback changes from 45° to 25°, and the drag coefficient increases by 45.5%. All the changes of sweepback have great influence on drag coefficient at transonic speeds. The influence of sweepback on lift-drag ratio is complex. In general, when the Mach number increases, the sweepback corresponding to the maximum lift-drag ratio increases. The altitude factor only has some influence on the drag coefficient at subsonic speeds. These aerodynamic change rules can provide a basis for the shape design and dynamic analysis of VMA.

1. Introduction
A variant is an object that changes its situation, shape, or character. Therefore, variant aircraft is a new type of aircraft that can change the aerodynamic layout so as to achieve good aerodynamic characteristics in different flight environments and conditions [1]. At the beginning of the 20th century, there were studies on variant aircraft in Britain, the United States and the Soviet union. Compared with fixed-wing aircraft, variant aircraft can take into account maneuverability, take-off and landing performance, penetration and assault performance and so on. In low speed flight, small swept wing is used to obtain better lift characteristics, while in hypersonic flight, large swept wing can achieve better lift and drag characteristics due to shock wave resistance. Therefore, it is difficult for a fixed aircraft configuration to meet all requirements.

At present, the key fundamental problems in the research of variant aircraft focus on the aerodynamic characteristics of variant aircraft, driving material and structure research, layout optimization design, stability and maneuverability, etc. The research on aerodynamic characteristics of variant aircraft is one of the most important fundamental researches.[2]
Around 2000, two far-reaching research projects on variant aircraft were launched at about the same time. NASA's variant project research is mainly to variant aircraft transformation mode and variant mechanism realization form exploration.[3] The DARPA is exploring the application of variant aircraft with folding and telescopic wings.[4-5] The new generation company's sliding skin wing solution USES a special flexible skin to deform the wing, changing its area by 70%[6]. The SmartWing program USES a continuous, smooth, non-hinged, high-deflection high-speed control surface to improve roll and pitch performance[7]. Many researchers have studied the aerodynamic characteristics and dynamic modeling of the variant aircraft. Yao et al.[8] studied the unsteady aerodynamic characteristics of the variable swept-back aircraft, and proved that the aerodynamic force caused by different swept-back speeds is not very different. Wang et al.[2] conducted the simulation of unsteady aerodynamic characteristics of a variable forward sweeping-wing aircraft, and summarized the variation rules of aerodynamic characteristics in the variation process. Neal et al.[9] studied the effects of variable elongation and variable sweepback on aerodynamic performance in low-speed flight through experiments. Secanell et al.[10] studied airfoil optimization in different flight states based on S-A turbulence model and CFD method. Liang et al.[11] proposed a switching control law based on the mode-dependent dwell time(MDDT), which ensured the stability of variant aircraft in the transformation switching process. Literature[12-13] constructed a switched linear parameter variable (LPV) model, transforming the complex system of variant aircraft into a linear switched model. Yuan et al.[14] conducted aerodynamic modeling and dynamic modeling of variant UAVS. He et al.[15] proposed a switching linear parameter varying based on the average dwell time method. According to the mission requirements of variant aircraft, this method divides the range of backward sweep into different regions.

The above researches on variant aircraft mainly focus on the subsonic stage, while few researches on transonic and supersonic stage. But variant aircraft make a lot of sense in transonic and supersonic designs. In flight, when the airflow speed is close to the speed of sound, the airflow speed on the upper surface of the wing will exceed the speed of sound, and the shock wave will rapidly increase the resistance. An aircraft with a greater forward reach would delay the shock wave, allowing the aircraft to travel at higher speeds. It is necessary to study variant aircraft in transonic and supersonic stages. However, according to the existing research situation, the flight resistance of the aircraft in the supersonic stage is large and the flow field is more complex, so the variation process usually ends before the supersonic stage. Therefore, this paper mainly studies transonic and subsonic phases. Based on the current research status, numerical simulation[16] and wind tunnel experiment [9] are mainly used for research. These two methods are time-consuming and costly in the early stage of aircraft design. This paper takes the VMA as the research object and adopts an engineering algorithm to analyze the aerodynamic characteristics at transonic speeds. The results can provide reference for the refined design and flight control system of VMA.

2. Shape design and aerodynamic characteristics calculation of VMA

2.1. Aerodynamic layout design of aircraft

The research object of this paper is the VMA, which adopts the normal layout. In order to simplify the calculation, based on the MiG-19 swept-back wing layout, some parameters were redesigned, and the original fixed wing design was changed to the variable wing design with "changing backward sweeping Angle". The fuselage is streamlined, with a length of 9.5m. When both the inside and outside sweepbacks are 45°, the wingspan is 4.1m and the airfoil area is 22.6m². The wing has an area of 22.6m², a tip chord length of 2.14m, a wing root chord length of 4.27m, and a shaft chord length of 2.56m. Airfoil NACA-W-6-66-012 was used for the wing, vertical tail and flat tail. Figure 1 shows the aircraft models corresponding to different sweepbacks.

The results show that the rotor position of the wing of a VMA has great influence on aerodynamic characteristics. If the rotation axis is more outward, the aerodynamic center movement will be significantly reduced, but the wing area that can be changed will be significantly smaller, unable to bring sufficient aerodynamic benefits. If the rotation axis is located close to the wing root, the area of the wing
that can be changed is larger, but this causes the shaft structure to gain weight, limit overload capacity, and make it difficult to rotate. Therefore, according to the current research on the VMA, we choose to set the position of rotation axis at 30% of the wingspan [17]. During the whole variation process, the inside sweepback remains 45°, while the outside sweepback changes from 25° to 75°.\[\chi_{\text{oo}}=25^\circ\text{ to }75^\circ\]

![Figure 1](image)

**Figure 1.** Aircraft models corresponding to different sweepbacks

### 2.2. Calculation method

After the shape of the aircraft is determined, the designer needs to know the aerodynamic force and torque acting on the aircraft. These data are determined by the geometric shape of the aircraft and directly affect the performance of the aircraft. Generally speaking, the general method is to conduct CFD calculation or wind tunnel experiment. However, wind tunnel experiments are expensive and CFD calculation takes a long time. Especially for the VMA, the sweepback, AOA and other parameters change during the calculation process. Neither approach is suitable for use in the early stages of aircraft design. The optimal situation is that the designer already has an aircraft that can meet the performance requirements. On this basis, the number of wind tunnel experiments and flight tests can be reduced to reduce the design cost.

The engineering algorithm can quickly estimate aerodynamic characteristics by means of analytic expressions. One of the better known is digital DATCOM software designed by the U.S. air force.[18] This exposed software takes airplane geometry as input. The input file should define the geometry of the fuselage, wings, flat tail, and vertical tail. A detailed description of the format of the DATCOM input file can be found in the digital DATCOM manual [19]. Once the input file is created, the DATCOM can be run to estimate the aerodynamic coefficients and derivatives of the selected aircraft shape and given flight conditions.

### 3. Results Analysis

#### 3.1. Lift characteristics of different sweepback Angles

##### 3.1.1. The influence of AOA on lift coefficient under different sweepbacks Angles

Figure 2 shows the curve diagram of the lift coefficient changing with the AOA under different sweepbacks when $M_a=1.0$. All the backward sweep models (BSMs) are not stalling. However, under small sweepback, the increase trend of lift starts to slow down when the AOA is 12°, while under large sweepback, the increase trend of lift does not slow down when the AOA is 14°. Therefore, it can be inferred that the stalling Angle of attack of small BSM is smaller than that of large. This is because the velocity component perpendicular to the wing is smaller under a large sweepback.

##### 3.1.2. The influence of Mach number on lift coefficient under different sweepback Angles

Figure 3 shows the curve diagram of the lift slop with Mach number at different sweepbacks. Under the same Mach number, the maximum lift of the small BSM is higher than that of the large. At the same inlet velocity, for the small BSM, the inlet velocity perpendicular to the wing is larger. In addition, there is also a shortage of leading edge lift in the large BSM. Therefore, the lift of small BSM is higher than that of large.

Under subsonic conditions (0.4, 0.6), the influence of small sweeping Angle on lift is greater than that of large sweepback on lift. In transonic condition (0.8, 1.0, 1.2), the influence of small sweepback
on lift is smaller than that of large sweepback on lift. The increase of Mach number changes the flow field and reduces the impact of shock wave under small sweepback.

Figure 2. Lift coefficient under different sweepbacks, $M_a=1.0$

Figure 3. Lift slope under different sweepbacks

As the Mach number increases, $C_{Le}^\alpha$ first increases and then decreases, reaching the maximum value near $M_a = 1.0$, remaining basically unchanged at subsonic speeds, changing rapidly at transonic speeds, decreasing slowly at supersonic speed, and the lift also shows the same trend.

3.2. Drag characteristics of different sweepback Angles

3.2.1. The influence of AOA on drag coefficient under different sweepback Angles. Figure 4 shows the curve diagram of the change of drag coefficient with the AOA under different sweepbacks when $M_a=1.0$. In the range from $-4^\circ$ to $0^\circ$, as the AOA increases, the drag of each model gradually decreases. Under the same AOA, the drag of small sweepback model is larger. At a small AOA, the drag characteristics are greatly affected by the change of sweepback at subsonic speeds. At high AOA, the drag characteristics are greatly affected by the change of sweepback at transonic speeds.

Figure 4. Drag coefficient under different sweepbacks, $M_a=1.0$

Figure 5. Drag coefficient with Mach number, AOA=12

3.2.2. The influence of Mach number on drag coefficient under different sweepback Angles. Figure 5 shows the curve diagram of the change of drag coefficient with Mach number under different sweepbacks when the AOA is $12^\circ$. Under different Mach Numbers, the drag of the small BSM is larger than that of the large. The reason is that at the same inflow velocity, the velocity component of the small back sweep model decomposed to the direction parallel to the wing is larger.
Under subsonic conditions (0.4, 0.6), the influence of small sweeping Angle on drag is greater than that of large sweeping Angle on drag. Under the transonic condition (0.8, 1.0, 1.2), all the changes of sweeping Angle have a great influence on the drag.

When the Mach number is lower than 0.6, the drag coefficient of each BSM increases slowly with the Mach number. Then the drag increases sharply with the increase of Mach number and then decreases and tends to be stable in the supersonic section. When the Mach number increases, the local shock wave is generated, the intensity increases and shock wave separation occurs, the drag increases rapidly. When the Mach number continues to increase, the drag coefficient decreases.

In the process of Mach number increasing from 0.8 to 1.0, the drag under a small sweepback increases sharply, while the drag under a large sweepback increases gently. The Mach number corresponding to the maximum drag coefficient increases with the increase of the sweepback. This is because the increase of the sweepback slows down the generation of shock waves. The sweepback is large, the effective partial velocity is small, the local shock wave is late, and the corresponding Mach number is large.

3.3 Lift-drag ratio characteristics of different sweepback Angles

Figure 6 shows the curve diagram of the lift-drag ratio with the AOA when the Mach number is 0.6, 1 and 1.4 respectively. When the Mach number is smaller ($M_a=0.6$), the lift-drag ratio of the small BSM is larger than that of the large BSM. This is because the lift of the small BSM is much larger than that of the large BSM, while the drag coefficient is less affected by the sweepback. This is particularly evident at small angles of attack.

![Figure 6. Lift-drag ratio with the AOA](image)

When the Mach number enters the transonic stage ($M_a>0.8$) and continues to increase, the lift-to-drag ratio advantage of the small BSM began to decrease. This is because the increase of Mach number will cause local shock waves on the wing surface, leading to a sharp increase in drag coefficient. A large sweepback can delay the generation of shock waves on the wing surface and reduce the drag coefficient. The lift-drag characteristics of the large BSM begin to show superiority.

Through the analysis of the lift-drag ratio, it can be found that the lift-drag ratio of the model with a sweepback of 75° is always low. Compared with the model with a sweepback of 65°, the lift coefficient of the model with 75° decreases more, but the drag coefficient is similar. Too large sweepback will not improve the lift-drag characteristics, but will make the lift-drag characteristics worse.

3.4 Effect of altitude

After a long period of exploration and summary, in the design process of aircraft, it is generally considered that height has little influence on lift force and pitching moment, but has a great influence on drag coefficient. Such treatment method is very suitable for fighter aircraft [20]. Figure 7 shows the curve diagram of drag coefficient with height at different sweeping Angles when the AOA is 12°.

At different flight altitudes, the change trend of drag with the change of sweeping Angle is the same, and different sweeping Angle will increase the same drag coefficient with the change of altitude. With
the increase of Mach number, the influence of altitude on drag decreases gradually, and becomes very weak at supersonic speed. When the AOA is 12°, the influence of altitude on the drag is nonlinear. When $M_a=0.6$ and the flight altitude changes from 17km to 22km, the increment of drag coefficient can reach 0.008 ~ 0.012. When $M_a=1.4$, the altitude changes by 20km, and the drag coefficient increases by 0.001 ~ 0.002 only.

4. Conclusion

Based on the above data, the following conclusions can be drawn about the aerodynamic characteristics of the VMA at different sweepbacks:

(1) For a given Mach number, when the sweepback increases, the slope of lift coefficient decreases, but the stalling AOA increases. For a given sweepback, when the Mach number increases, the lift first increases and then decreases. Under the subsonic condition (0.4, 0.6), a small sweepback has a greater impact on the lift. When the AOA is 12°, the sweepback changes from 45° to 25°, and the lift coefficient increases by 48.9%. Under the transonic condition (0.8, 1.0, 1.2), a large sweepback has a greater impact on the lift. When the AOA is 12°, the sweepback changes from 75° to 55°, and the lift coefficient increases by 85.7%.

(2) For a given Mach number, the drag coefficient decreases when the sweepback increases. For a given sweepback, when the Mach number increases, the drag first increases and then decreases. Under the subsonic condition (0.4, 0.6), the drag is almost constant. Under transonic conditions (0.8, 1.0, 1.2), the drag coefficient under small sweepback increases sharply with Mach number, while the drag coefficient under large sweepback increases gently.

(3) The changes of aerodynamic parameters under different BSMs are complex. When the lift-drag ratio is selected as the index to measure aerodynamic benefits, the optimal sweepback increases with the increase of Mach number, but the optimal sweepback is not a linear relationship with the Mach number. There is a maximum sweepback of 75°, under which the aerodynamic effect is not satisfactory.

(4) Altitude has a low influence on lift coefficient, but a large influence on drag coefficient at subsonic speeds. When studying the variable swept-back rule, the influence of height on aerodynamic characteristics under subsonic conditions should be considered to modify the variable swept-back rule.

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