AERODYNAMIC ANALYSIS AND ROLL CONTROL ALLOCATION FOR ASYMMETRIC VARIABLE SWEEP AIRCRAFT WITH FLEXIBLE TRAILING EDGE

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Abstract
The maneuverability of aircraft can be enhanced by changing the sweep angle and camber of wings separately. Using the method of computational fluid dynamics, the feasibility of the combined differential deflection of the generalized control surfaces for rolling maneuver is verified firstly. In addition, roll efficiency functions of redundant lateral control surfaces under different working conditions are established. After that, the dynamics equations of ideal rolling maneuver subsystem are established by using Kane's methods. Based on the aerodynamic analysis results and dynamics equations, the control allocation weights of asymmetric sweep aircraft with flexible trailing edge under the framework of Supervisory-Main Controller are determined. In the end, control laws of main and supervisory controllers are derived. Analysis results show that using redundant control surfaces can effectively increasing roll moment and avoid controller turning into saturation state, which will improve the control efficiency inside the whole flight envelope.

1 Introduction
With the development of aviation technology, future war requires aircraft to have better overall performance in multiple missions. However, there's no significant improvement in aircraft maneuverability when using traditional control surfaces. In order to achieve the ability of predation, evading predators and migration, birds have acquired the extraordinary flying ability and high flight efficiency through a long process of evolution. As the research of the flight characteristics of birds and winged insects moves along and the development of intelligent materials, the concept of intelligent morphing aircraft comes into being. Intelligent morphing aircraft can smoothly and autonomously change partial or integral of its shape through the integrated application of intelligent materials, actuators, sensors, actuators and other advanced technologies in different flight conditions for improving the overall flight performance and expanding the flight envelope[1~3].

As the main component of aerodynamic generation, the researches on asymmetric morphing aircraft are mainly focus on the wing deformation mechanism. A rich body of studies have shown that asymmetric changes of sweep angle, span and camber can all be used as the control inputs for maneuvering and play the same role as the traditional control surfaces [4~7]. It can be found by observing the flight posture change of swifts, pigeons and seagulls that there's always the combination of large and medium deformation of the flexible wing during the flight[8~10]. This combinatory deformation strategy provides a new train of thought for further improving the roll control efficiency of aircraft. Fig.1 shows the wing deformation of sea gulls between the right and left wings along with the inboard and outboard.

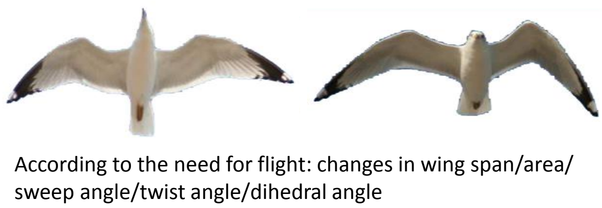


Fig. 1 Wing Shape Change of Sea Gull During Flight[10]

In order to avoid the position and rate saturation of control surfaces, it is necessary to carry out control allocation design for redundant control systems with large deformation as additional inputs[11~12]. At present, the researches on asymmetric sweep aircraft with flexible trailing edge are mainly focus on qualitative analysis of aerodynamic characteristics and establishment of dynamic modes[13~15]. The quantitative comparative analysis of aerodynamic characteristics between the flexible trailing edge and sweep angle is lacking. In order to have efficient utilization of the two generalized control surfaces, the influence factors of control efficiency need to be analyzed firstly. Then, roll efficiency functions are also needed to be established and control allocation strategies need to be established under different working conditions.

In this paper, the problem of roll control allocation of asymmetric sweep aircraft with flexible trailing edge is studied. Firstly, aerodynamic characteristics for both generalized control surfaces are studied and the roll control efficiency functions are established. By the study of aerodynamic characteristic of multiple combined differential deflection modes of redundant generalized control surfaces, a reasonable and high-efficiency roll control strategy is provided. Then, dynamic models for ideal roll subsystem are established by using Kane's methods. With sweep angle change as the supervisory controller, the Supervisory-Main Controller architecture is selected to realize control distribution design. The methods of determining the value of weight factors for control surfaces are determined under different situations. Finally, control laws of main and supervisory controllers are derived. The specific research approach of this paper is shown in Fig.2.

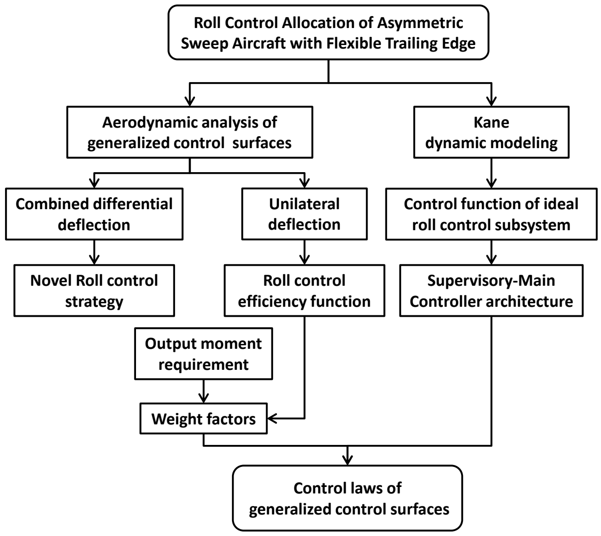


Fig. 2 Research Approach of Roll Control Allocation of Asymmetric Morphing Aircraft

2 Efficiency Functions of Generalized Control Surface

To take the best use of sweep angle change and flexible trailing edge deflection for roll maneuver, the aerodynamic characteristics of two generalized control surfaces should be studied firstly. In consideration of the shape requirements for airfoil in different heights and velocities, NACA 0006 is selected for wings modeling. The wings are rectangular in shape, and the parameters are shown in Table.1.

Table.1 Model Parameters Value

Parameters	Value
Half span(b/2)	4*m*
Chord length(c)	1*m*
Trailing edge chord length	0.25*m*
Trailing edge spanwise length	4*m*

Besides, the deflection of flexible trailing edge requires continuous and smooth change of the shape by the drive of multiple actuators along the spanwise direction when subjecting to aerodynamic loads[16,17]. This driving mode may cause the unequal deflection angle of trailing edge along the span due to mechanism stuck and insufficient of driving force at some sections. Therefore, this unique deflection mode of flexible trailing edge needs to be analyzed. In this paper, five typical flexible trailing edge deflection modes are selected for modeling and analyzing. The deflection angle for each mode is shown in equation(1).

$$\delta_{TE(0\le y\le 4)}=\begin{cases}0,5,10,15 & state1\\ 3.75\left\|y\right|-4\right| & state2\\ 3.75\left|y\right| & state3\\ 3.75\left\|y\right|-4\right| & state4\\ 3.75\left|y\right| & state5\end{cases} \quad (1)$$

where y represents the spanwise coordinate in body axis system. State1 represents equiangular deflection of trailing edge, and the deflection angles are respectively equals 0°, 5°, 10° and 15°. State2 and state3 respectively represents the downward deflection angle of trailing edge from root to tip, and the range of deflection angle is 0~15°. State4 and state5 respectively indicates the upward deflection angle of trailing edge from root to tip. In practice, it is just the sweep angle change near the tip of the wing, and trailing edge non-equiangular deflection modes can simulate this situation to some extent. In this paper, various wing reference models under different sweep angles and trailing edge deflection modes are established. Numerical aerodynamic calculation methods are used for analyzing the variation of aerodynamic force and moment and establishing the efficiency function for two generalized control surfaces, where the reference point of moment is taken as the leading edge of wing root. The Mach numbers are respectively 0.2, 0.4 and 0.6. The angle of attack is range from 0° to 20° and sweep angle is range from 0° to 30°.

2.1 Aerodynamic Characteristics of Control Surfaces

Fig.3 shows the variation of roll moment coefficient with lift coefficient that caused by the asymmetric change of sweep angle change in different Mach numbers while sweep angle of left wing remains 0°. It can be found that the roll moment coefficient increases approximately linearly with the lift coefficient before flow separation. At the same time, it can be seen that Mach number has little effect on the roll moment under the same lift coefficient.

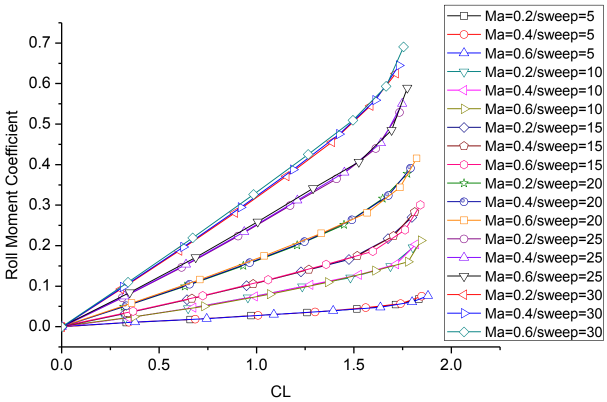
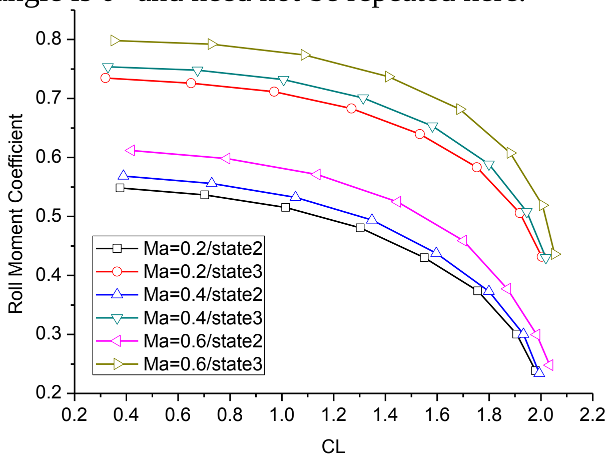
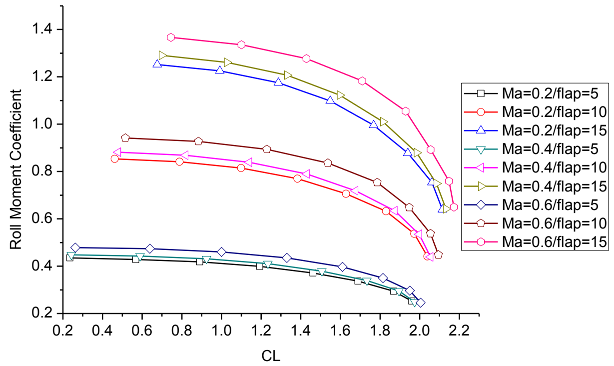


Fig.3 Roll Moment Coefficient Generated by Asymmetric Sweep Change

Fig.4 shows the variation of roll moment coefficient caused by different trailing edge deflection modes and the sweep angle remains 0°.Unlike the case of using the change of sweep angle for roll maneuver, roll moment coefficient caused by the deflection of flexible trailing edge decreases nonlinearly with lift coefficient. In general, the higher the Mach number and the bigger the deflection angle, the faster the value of roll efficiency decreases. Furthermore, the effect of the trailing edge deflection modes on roll moment coefficient is greater than that of Mach numbers. For a given lift coefficient, the roll moment generated by state3 is significantly greater than that of state2. After the separation of airfoil flow, roll control efficiency of trailing edge in state3 decreases much faster than in state2. The variation of roll moment under other sweep angles is similar to that under the sweep angle is 0° and need not be repeated here.



(a) Unequal Angle Deflection of Trailing Edge



(b) Equal Angle Deflection of Trailing Edge
Fig.4 Roll Moment Coefficient Generated by Various Trailing Edge Deflection Modes

Fig.5 shows the variation of yaw moment coefficient with lift coefficient that caused by the sweep angle change of single right wing in different Mach numbers while the sweep angle of left wing remains 0°. For conditions of a same asymmetric change of sweep angle, the yaw moment increases approximately linearly with lift coefficient. However, the larger the asymmetric sweep angle, the slower the yaw moment coefficient increase under the same lift coefficient. It can also be found that Mach numbers have little effect on yaw moment under the same lift coefficient.

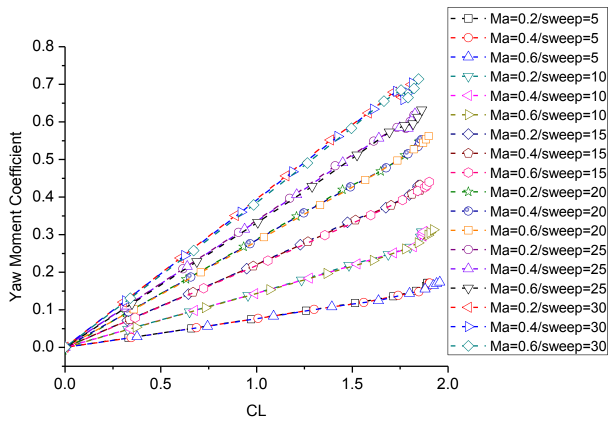
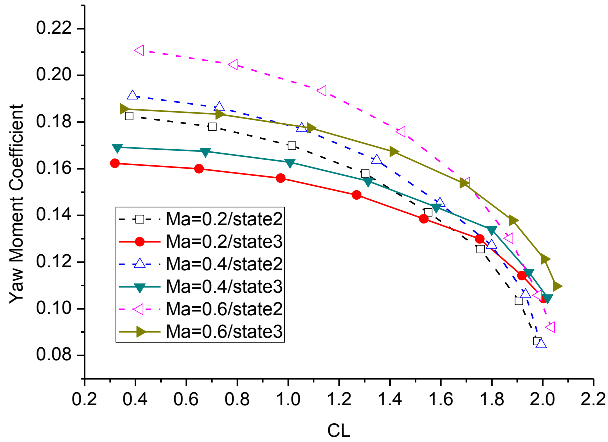
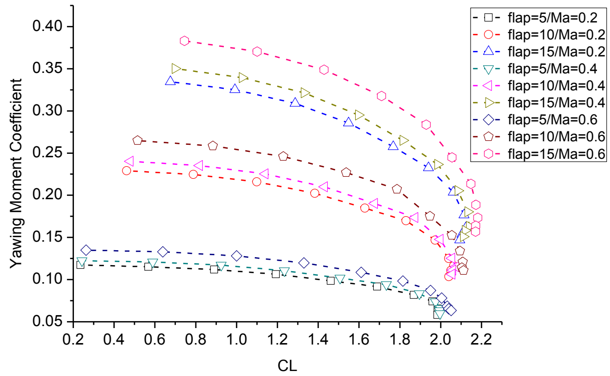


Fig.5 Roll Moment Coefficient Generated by Asymmetric Sweep

Fig.6 shows the variation of the yaw moment coefficient under different trailing edge deflection modes when the sweep angle of wings equals zero. Unlike asymmetric change of the sweep angle, yaw moment caused by the deflection of the flexible trailing edge decreases nonlinearly with the increase of the lift. Generally speaking, the greater the Mach numbers and the trailing edge deflection angle, the greater the yaw moment. The influence of trailing edge deflection on yaw moment is greater than Mach numbers. By comparing two trailing edge non-equiangular deflection modes (state2 and state3), the yaw moment of state3 is smaller than that of state2 when lift coefficient is small. When lift coefficient is larger and the flow is separated, the yaw moment of state3 becomes larger than that of state2



(a) Unequal Angle Deflection of Trailing Edge



(b) Equal Angle Deflection of Trailing Edge
Fig.6 Roll Moment Coefficient Generated by Various Trailing Edge Deflection Modes

Above all, we can conclude that roll control capability of flexible trailing edge is greater than that of sweep angle change when angle of attack is small. With the increase of lift and trailing edge deflection angle, the decreasing speed of roll control capability of flexible trailing edge increase gradually, while the roll control capability of sweep angle increases linearly. Either wash-in or the change of the sweep angle change is a feasible and efficient roll control method when lift coefficient is large. When lift coefficient is large, large trailing edge deflection angle also produce a large yawing moment. In this situation, increasing the sweep angle will make the total yaw moment smaller.

2.2 Aerodynamic Analysis of Combined Differential Deflection of Control Surfaces

In practice, to eliminate the effects of yawing caused by the lateral control surfaces, differential deflection of lateral control surfaces is usually adopted to balance the induced drag by increasing the form resistance. According to the previous analysis, flexible trailing edge control surfaces should be preferentially selected in actual flight. When high lift of aircraft results in the lower roll efficiency of the flexible trailing edge or the output moment cannot meet the control needs, asymmetric change of sweep angle should be used. Therefore, it is necessary to analyze the unique combined differential deflection mode of flexible trailing edge and sweep angle change. The combined differential deflection mode involve in this paper are shown in Fig.7

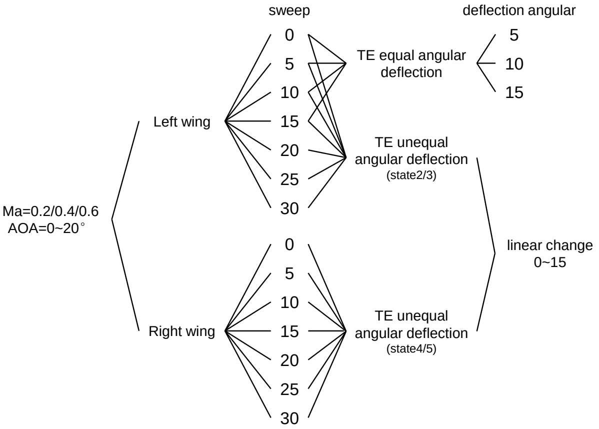
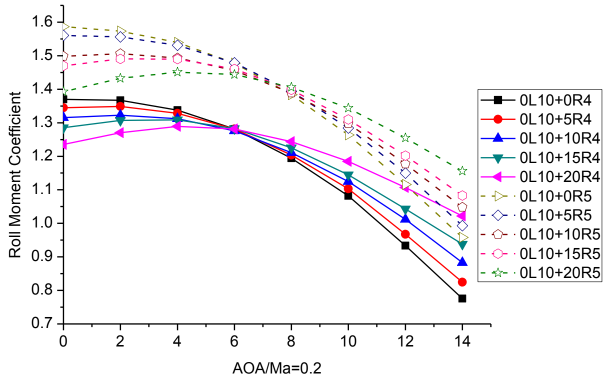
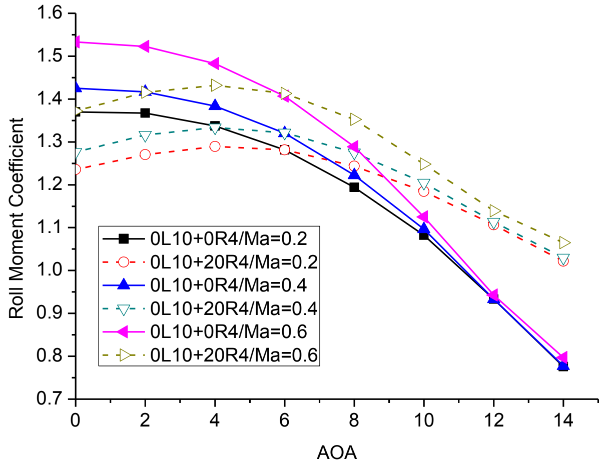


Fig.7 Combined Differential Deflection Modes in This Paper

Fig.8 represents the variation of roll moment with angle of attack under different Mach numbers where the trailing edge deflection angle of the left wing is 10° and the deflection modes of the right wing trailing edge are state4 and state5. The sweep angle of the left wing is 0°and the sweep angle of the right wing range from 0° to 20°. It can be seen that the trailing edge deflection mode of state5 enables the aircraft to obtain greater roll moment. When the angle of attack is small, the bigger the sweep angle of the right wing is, the less roll moment is generated. However, when the angle of attack increases to a certain value, the bigger the sweep angle of the right wing, the bigger the roll moment is generated. The roll moment increases gradually with the increase of the Mach number when given the deflection state of the control surfaces of left and right wings. With the increase of angle of attack, the difference of roll moment between different Mach numbers decreases gradually.



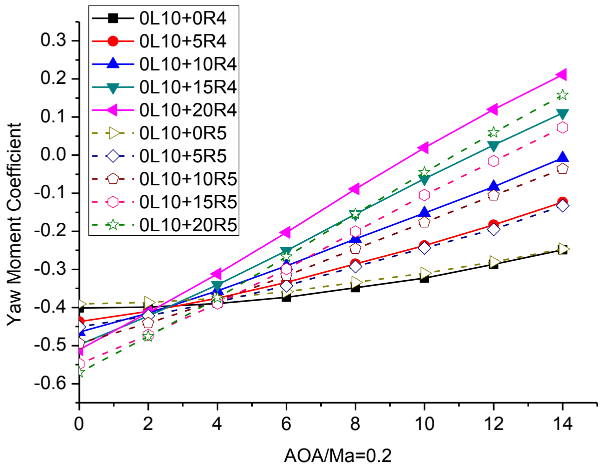
(a)



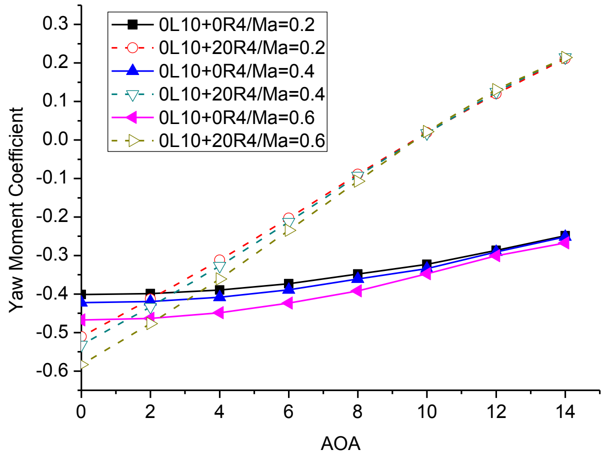
(b)

Fig.8 Variation of Roll Moment Coefficient with Angle of Attack under Different Mach Numbers

Fig.9 represents the variation of yaw moment with angle of attack under different Mach numbers where the trailing edge deflection angle of the left wing is 10° and the deflection modes of the right wing trailing edge are state4 and state5. It can be seen that the yaw compensation moment generated by asymmetric sweep angle change increases gradually with angle of attack. The total yaw moment appears to change sign when the asymmetric sweep angle and angle of attack are large enough. In general, the yaw compensate moment produced by two upper deflection modes of the right wing has little differences under the same deflection modes of the control surfaces. It also can be seen that the bigger the angle of attack, the more significant the yaw compensation effect caused by asymmetric sweep angle change is.



(a)



(b)

Fig.9 Variation of Yaw Moment Coefficient with Angle of Attack under Different Mach numbers

To sum up, the combined differential deflection of flexible trailing edge and asymmetric change of sweep angle is a unique and more efficient roll control method which can output larger control moment and has smaller course trimming moment. Comparing the roll and yaw moment characteristics of trailing edge deflection modes (state4 and state5), we can conclude that tip have larger upper twist angle and sweep angle change under large lift coefficient are both efficient strategies for roll control. Other combined differential deflection modes are similar to the models in this paper and will not repeated here.

2.3 Roll Efficiency Function Establishment

Referring to the definition of control efficiency of aileron, before the separation of airfoil flow, the control efficiency of the generalized control surfaces can be expressed as the derivative of the roll moment coefficient with the generalized deflection angle of control surfaces[17]:

$$C_{l\Lambda} = \partial C_l / \partial \Lambda = a\Lambda^2 + b\Lambda + c$$
$$C_{l\delta} = \partial C_l / \partial \delta = d \qquad (2)$$

where δ represents the deflection angle of flexible trailing edge. Variable parameters (a,b,c and d) are constant under the given Mach number, sweep angle and angle of attack. The detailed expressions of generalized control surfaces control efficiency under different working conditions are listed in Appendix A. Table.2 shows the variation of roll control efficiency of sweep angle change under different Mach numbers and angles of attack. Table.3 shows the variation of roll control efficiency of flexible trailing edge under different Mach numbers, sweep angles, and angles of attack. It can be seen that roll control efficiency of flexible trailing edge doesn't change with deflection angle. However, under a given Mach number and angle of attack, the roll efficiency of the sweep generalized control surface nonlinearities variation with sweep angle.

3 Roll Control Allocations of Redundant Control Surfaces

3.1 Aircraft Geometry Model

In this paper, the aircraft is simplified into three independent rigid bodies: the fuselage, the left wing and the right wing, and the mass for each body are respectively as m_f, m_w and m_w. The fuselage is simplified into a homogeneous cylinder with length of l_f and radius of R_f, and the center of mass is remarked as O_{FL}. The left and right wings are simplified into two uniform thin rods with a length of l_w. The center of mass for wings are respectively remarked as O_L and O_R. Taking $O_1$and O_2 as the circle center for both sides of wing, and the sweep angle is respectively remarked as Λ_L and Λ_R. In order to simplify the model, the equivalent wing rod is assumed to be located in the symmetrical plane of the fuselage, which is also the longitudinal inertia principal axis plane of the fuselage. The body coordinate system is established with the center of mass of fuselage O_{FL} as the original point, which is shown in Fig.10.

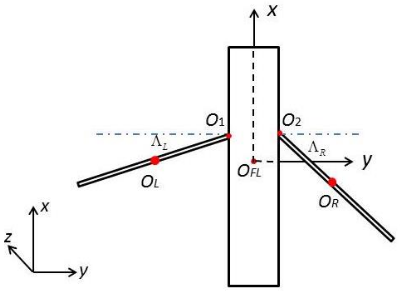


Fig.10 Models of Asymmetric Variable Sweep Aircraft

3.2 Establishment of Roll Subsystems Dynamic Model

The independent degrees of freedom of the research object system is 8. Therefore, we select the coordinates of O_{FL} in the ground coordinate system and the pitch, yaw, roll angles along with the sweep angle for both sides of the wing of the body system relative to the ground system as the generalized coordinates, which is defined as $(x,y,z,\theta,\psi,\Phi,\Lambda_L,\Lambda_R)$. Choosing the projection of the translational velocity of point O_{FL} in ground system onto the body system (u,v,w) and the component of angular velocity of rotation of the body system relative to the ground system on the body axis (p,q,r) and the derivative of the sweep angle with respect to time as the generalized velocity, which is defined as $(u,v,w,p,q,r,\eta_L,\eta_R)$.

External forces on the fuselage body include gravity $\boldsymbol{G}_f$, engine thrust $\boldsymbol{T}$ and resistance $\boldsymbol{D}_f$. The thrust direction of the engine is set along the longitudinal direction of the fuselage, so thrust does not create moment which relative to the coordinate system's origin. Since the fuselage contributes little to the lift, the lift generated by fuselage is ignored in the preliminary analysis. In addition, the fuselage body is subjected to torque $\boldsymbol{T}_L$ and $\boldsymbol{T}_R$ by the deflection devices of wing located at O_1 and O_2.

External forces on the wing body include gravity $\boldsymbol{G}_w$, lift $\boldsymbol{L}_w$, resistance $\boldsymbol{D}_w$ and the torque $-\boldsymbol{T}_L$ and $-\boldsymbol{T}_R$ produced by the actuator at the wing body joint.

Based on the Kane's methods which described in reference.15, in the case of an asymmetric morphing mode where the sweep angle of the left wing is zero and the sweep angle of the right wing changes independently, the governing equation of ideal rolling maneuver is established without considering the coupling effect with pitch, side sliding and other motions.

$$\begin{cases} \dot{\boldsymbol{x}}_1 = \boldsymbol{x}_2 \\ \dot{\boldsymbol{x}}_2 = f(\boldsymbol{X}) + g(\boldsymbol{X})\boldsymbol{U} \end{cases} \tag{3}$$

where $f(X)=(\boldsymbol{K}_\Omega)^{-1}(\boldsymbol{J}_A\boldsymbol{D}_f+\boldsymbol{E}_G^1\boldsymbol{G}_w+\boldsymbol{E}_G^2\boldsymbol{G}_f-\boldsymbol{N})$, $\boldsymbol{x}_1=\Phi$, $\boldsymbol{x}_2=p$, $\boldsymbol{g}(X)=[\boldsymbol{L}_\delta \ \ \boldsymbol{L}_\Lambda]$, $\boldsymbol{U}=[\boldsymbol{\delta} \ \ \Lambda]^T$. The multiplying results of $\boldsymbol{g}$ and $\boldsymbol{U}$ indicate the roll moment generated by the change of aerodynamic force, which can be calculated by the above results obtained by the Fluent calculation results. The dimension of coefficient matrix $\boldsymbol{J}_A$, $\boldsymbol{E}_G$ and $\boldsymbol{K}_\Omega$ are respectively 8×1, 8×2 and 8×1 and the items are functions of trigonometric functions of α and Φ and other parameters of the model. The dimension of matrix $\boldsymbol{N}$ is 8×1 which items are consist of the cross terms and the square terms of the generalized velocity (see Appendix B). It can be found from the dynamic model that neither the thrust nor the torque for sweep angle change will affect the roll motion of the aircraft. Due to the asymmetric change of the sweep angle, the center of gravity of the aircraft is shifted. So the resistance and gravity of fuselage will also generate additional moment to rolling maneuver.

3.3 Determination of Control Allocation Weights

In this paper, sweep angle change is imported as a new attitude controller and this involves the problem of redundant control allocation. The change of sweep angle causes dramatically change in aircraft aerodynamic characteristics and has great influence on aircraft stability and maneuverability, which is not suitable to be as conventional control surfaces. Based on this situation, we choose the Supervisory-Main controller architecture for redundant control allocation design. This architecture can add an auxiliary controller to stable system without changing the original control design and guarantee the global stability of the system[18].

The second equation of the roll subsystem can be rewritten as:

$$\dot{x}_2 = f(X) + h(X) + (K_\Omega)^{-1} L_\delta(\delta + \frac{L_\Lambda}{L_\delta}\Lambda) \quad (4)$$

According to the previous analysis, flexible trailing edge deflection is selected as the main controller and the compensation deflection is carried out using the sweep angle change when the control capability drops due to the failure of the deflection mechanism or the maximum deflection of flexible trailing edge is still insufficient to meet the needs for maneuver. Defining the main controller $u_M=\delta$ and the supervisory controller $u_s=(L_\Lambda/L_\delta)\Lambda$, thus the total control quantity can be expressed as:

$$u = (1-H)\cdot u_M + H\cdot u_s \quad (5)$$

When the deflection and roll speed are not large, it can be considered that there is no interference between control surfaces on different side of wings. The total moment is the sum of roll moments generated by the single action of control surfaces on both sides[17]. The control weights H can be decided by the following procedures:

1) The initial sweep angle of aircraft and flight conditions such as Mach number and angle of attack should be determined firstly. As flexible trailing edge deflection can provide superior roll control when lift coefficient is small, thus the deflection of flexible trailing edge is chosen as the main controller.
2) If the maximum deflection of trailing edge can meet the needs for rolling maneuver, we should compare the control capability for both control surfaces. If the roll control moment of flexible trailing edge is larger than sweep angle change, the control weight H equals 0, which means the asymmetric sweep angel change is 0.
3) If the moment contributed by single use of trailing edge deflection can't satisfy the requirement for rolling maneuver, we should also compare the control capability for two kinds of generalized control surfaces. The control weights H for roll maneuver after the intersection point satisfies the equation

$$H = Cl_{sweep}/(Cl_{sweep}+Cl_{flap}) \quad (6)$$

All required values can be acquired from Table.2 and Table.3. Thus we can get the change of asymmetric sweep angle.

3.4 Control laws for generalized control surfaces

Based on the methods that described in reference.19, control laws for the main controller (flexible trailing edge) can be described as:

$$u_M = \frac{1}{L_\delta}\left[-\left(k^2+1\right)\phi - \left(f+h\right) - 2kp\right] \quad (7)$$

where k is constant and should be determined by actual system.

Defining $g_L=L_\delta$、 $\boldsymbol{b}=[0\ L_\delta]^T$, and control laws for the supervisory controller can be described as:

$$u_s = -sign\left(\boldsymbol{X}^T \boldsymbol{pb}\right)\left[\frac{1}{L_\delta}\left(f^U + \left|\boldsymbol{k}^T\boldsymbol{X}\right|\right) + \left|u_M\right|\right] \quad (8)$$

4 Conclusions

In this paper, a new roll control strategy by the integrated use of flexible trailing edge deflection and sweep angle change is discussed. Base on the roll control efficiency function established by aerodynamic numerical simulation methods, the control allocation methods for asymmetric variable sweep aircraft with flexible trailing edge are studied. The main conclusions are as follows:

(1) According to the previous analysis, it can be seen the roll control efficiency of sweep angle increases nonlinearly with the increase of sweep angle, and the roll control efficiency of flexible trailing edge is constant. Flexible trailing edge deflection has better roll control capability when lift is small. When the roll control capability of provided by trailing edge deflection drops due to the failure of the deflection mechanism or the maximum deflection is still insufficient to meet the need for maneuver, asymmetric change of sweep angle can apply additional compensation moment. The established roll control efficiency functions for generalized control surfaces can be used as a reference for the design of the same type of aircraft.

(2) Larger deflection angle of trailing edge produces larger yaw moment, in this situation, a modest increase of the sweep angle will make the total yaw moment

smaller. By comparing the aerodynamic characteristics of two non-equiangular deflection modes of trailing edge, it can be concluded that either wash-in or the change of the sweep angle change is a feasible and efficient roll control method when lift coefficient is large. The combined differential deflection of flexible trailing edge and asymmetric change of sweep angle is a unique and more efficient roll control method which can output larger control moment and has smaller course trimming moment.

(3) By proper simplification, the dynamic control equation for ideal rolling maneuver with sweep angle variation on one side is established. According to the equation, the parameters influencing the aircraft rolling maneuver include wing lift, wing resistance, fuselage resistance, wing gravity and fuselage gravity. Unlike conventional aircraft, control surfaces deflection angular, control surfaces deflection angular velocity, aircraft roll angular and aircraft roll angular velocity also have impacts on rolling maneuver. The dynamic model can be used as the basis for the dynamics analysis and control system design of the same type of aircraft.

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Appendix A

Table.2 Roll Control Efficiency of Sweep Angle

AOA	Ma=0.2	Ma=0.4
2	$-0.0976\Lambda^2+0.4988\Lambda+0.0484$	$0.26835\Lambda^2+0.6358\Lambda+0.0344$
4	$0.3126\Lambda^2+0.6026\Lambda+0.170$	$0.17586\Lambda^2+0.7362\Lambda+0.1645$
6	$0.3357\Lambda^2+0.9192\Lambda+0.2639$	$0.3336\Lambda^2+0.9698\Lambda+0.278$
8	$0.9201\Lambda^2+0.7868\Lambda+0.4307$	$0.8877\Lambda^2+0.864\Lambda+0.444$
10	$0.4245\Lambda^2+1.3448\Lambda+0.4856$	$0.6591\Lambda^2+1.221\Lambda+0.5354$
12	$1.0425\Lambda^2+0.6524\Lambda+0.8105$	$0.7461\Lambda^2+0.8638\Lambda+0.8049$
14	$1.0575\Lambda^2+0.06316\Lambda+1.142$	$-0.6123\Lambda^2+1.0834\Lambda+1.042$
AOA	Ma=0.6	
2	$-0.4092\Lambda^2+0.7688\Lambda+0.0345$	
4	$-0.1853\Lambda^2+1.0576\Lambda+0.1542$	
6	$-0.2893\Lambda^2+1.4896\Lambda+0.2547$	
8	$-0.0790\Lambda^2+1.6172\Lambda+0.3984$	
10	$-0.0522\Lambda^2+1.7348\Lambda+0.5414$	
12	$-1.3317\Lambda^2+2.184\Lambda+0.698$	
14	$-1.0071\Lambda^2+1.3995\Lambda+1.092$	

Table.3 Roll Control Efficiency of Flexible Trailing Edge

	Sweep=0			Sweep=5		
AOA	Ma=0.2	Ma=0.4	Ma=0.6	Ma=0.2	Ma=0.4	Ma=0.6
0	4.681	4.83	5.093	4.633	4.756	5.005
2	4.566	4.691	4.941	4.5	4.615	4.851
4	4.338	4.446	4.678	4.269	4.367	4.586
6	4.005	4.081	4.284	3.935	4.01	4.206
8	3.578	3.62	3.771	3.489	3.519	3.654
10	3.1	3.095	3.108	2.968	2.95	3.01
12	2.634	2.602	2.649	2.45	2.382	2.375
14	2.214	2.252	2.314	1.964	1.941	1.939
	Sweep=10			Sweep=15		
AOA	Ma=0.2	Ma=0.4	Ma=0.6	Ma=0.2	Ma=0.4	Ma=0.6
0	4.209	4.331	4.58	3.923	4.031	4.242
2	4.079	4.194	4.431	3.797	3.896	4.096
4	3.862	3.961	4.176	3.584	3.667	3.849
6	3.551	3.626	3.811	3.278	3.337	3.487
8	3.147	3.185	3.312	2.905	2.921	2.978
10	2.67	2.642	2.629	2.482	2.46	2.428
12	2.183	2.14	2.109	1.823	1.799	1.825
14	1.878	1.822	1.869	1.387	1.413	1.505

Appendix B

The fuselage is simplified into a cylinder with a radius of R_f and a length of Lf. The wing is simplified into a slender rod with a length of L_w. The coordinates of hinged point between the wing and the fuselage in body axis system are respectively defined as $(h,-R_f,0)$ and $(h,R_f,0)$. The aircraft angle of attack is defined as α. The sweep angle of the left wing is defined as Λ_R. η is the angular velocity of sweep angle change.

$$J_A = \begin{bmatrix} -\cos\alpha \\ 0 \\ -\sin\alpha \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} \quad E_G = \begin{bmatrix} -\sin\alpha & -2\sin\alpha \\ \sin\phi\cos\alpha & 2\sin\phi\cos\alpha \\ \cos\phi\cos\alpha & 2\cos\phi\cos\alpha \\ 0 & 0 \\ 0 & -2h\cos\phi\cos\alpha \\ 0 & 0 \\ 0 & 0.5l_w\sin\alpha(1+\cos\Lambda_R)-0.5l_w\sin\phi\cos\alpha\sin\Lambda_R \\ 0 & 0 \end{bmatrix}$$

$$K_\Omega = \begin{bmatrix} 0 \\ 0 \\ 0.5m_w l_w(1-\cos\Lambda_R) \\ -I_{fx}-2m_w R_f^2-0.5m_w R_f l_w(1+\cos\Lambda_R)-I_{lx}-\cos^2\Lambda_R I_{rx}-\sin^2\Lambda_R I_{ry} \\ 0.5m_w h l_w(\cos\Lambda_R-1)-\sin\Lambda_R\cos\Lambda_R\eta\left(I_{rx}-I_{ry}\right) \\ 0 \\ 0 \\ 0 \end{bmatrix}$$

$$N = \begin{bmatrix} -0.5m_w l_w\eta^2\sin\Lambda_R \\ 0.5m_w l_w\left(\eta^2+p^2\right)(\cos\Lambda_R-1) \\ 0.5m_w l_w\eta p\sin\Lambda_R \\ 0.5m_w R_f l_w\eta p\sin\Lambda_R-p\sin\Lambda_R\cos\Lambda_R\eta\left(I_{ry}-I_{rx}\right) \\ -0.5m_w h l_w\eta p\sin\Lambda_R-p\sin^2\Lambda_R\eta I_{ry}+p\eta I_{lx}-p\cos^2\Lambda_R\eta I_{rx}+p\eta I_{rz}-p\eta I_{lz} \\ -p^2\sin\Lambda_R\cos\Lambda_R\left(I_{rx}-I_{ry}\right)+0.5m_w l_w R_f\eta^2\sin\Lambda_R+0.5m_w h L_w\left(\eta^2+p^2\right)(\cos\Lambda_R-1) \\ 0.25m_w l_w^2\eta^2\sin\Lambda_R+0.5m_w l_w\left[-p^2R_f\sin\Lambda_R-0.5l_w\left(\eta^2+p^2\right)(\sin\Lambda_R\cos\Lambda_R)\right] \\ -p^2\sin\Lambda_R\cos\Lambda_R\left(I_{rx}-I_{ry}\right) \end{bmatrix}$$

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