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SIMULATION ON THE EFFECT OF AIRCRAFT LOCAL STRUCTURE DAMAGES ON THE DYNAMIC DERIVATIVE COUPLING CHARACTERISTICS

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Abstract

The aircraft "injured but not destroyed" by various warheads should maximize the use of the remaining lift, thrust and other components to achieve self-rescue. The most critical point is to master the dynamic aerodynamic characteristics of the damaged configuration, which provides a basis for the reconfiguration control strategy of damaged aircraft. In this paper, the high-precision CFD method is used to simulate the dynamic derivative coupling characteristics of different damaged configurations. The concepts of "longitudinal-lateral" and "lateral-longitudinal" coupling dynamic derivatives of asymmetric damaged aircraft are analyzed based on the principle of flight mechanics. The typical flying wing configuration is taken as the research object, then the dynamic simulation of longitudinal and lateral small amplitude harmonic rotation is carried out, and we identified the coupled dynamic derivatives in this direction. The results show that after asymmetric damage, the lateral cross derivative is induced longitudinally and increases with the increase of damage area. The dynamic derivative has a low value in a certain angle of attack range, which forms a favorable range for the reconfiguration of the control and stability. The longitudinal coupling effect induced by lateral motion also increases with the increase of the defect area, especially the large area component missing caused by continuous rod warhead, which can cause obvious "lateral- longitudinal" coupling effect.

Keywords: damaged configurations; coupling dynamic derivatives; unsteady aerodynamics; flying wing; Computational Fluid Dynamics(CFD)

1. Introduction

Modern battlefield environment poses a greater threat to the survivability of flight vehicles. Various ground air defense firepower and air-to-air missiles bring the consequence that either the flight vehicle is completely destroyed, or the local damage on the components decrease its survivability[1-3]. Clearly, from the perspective of users, it is hoped that the local-damaged vehicles can return safely to improve the utilization level of the overall equipment, and the premise of achieving this goal is to accurately obtain the performances of the damaged aircraft, especially the dynamic aerodynamic characteristics[4-5].

Compared with the static aerodynamic characteristics, the dynamic aerodynamic forces are more sensitive to the stability quality, which directly affects the formulation of the control strategy of the damaged aircraft. Therefore, this paper focuses on the dynamic derivative, which is one of the key parameters of dynamic aerodynamics. Compared with conventional non-destructive aircraft, the symmetry of aircraft configuration after battle damage is broken, resulting in the coupling dynamic derivative term different from conventional aircraft. However, the related coupled dynamic stability caused by local damage of configuration is rarely concerned. In the previous research[6], the author took SACCON flying wing model as an example to carry out the identification of static and "longitudinal-lateral" coupling dynamic derivatives of war damaged aircraft. The results show that with the different damage configurations, the coupling characteristics between "longitudinal-lateral" are also different, which generally reflects that with the increase of the missing area, the coupling characteristics become more serious, threatening the control and stability of the damaged but still usable aircraft. However, this study only focused on the "longitudinal-lateral" coupling, and did not regard other coupling dynamic derivatives. In fact, there are many coupling terms, and its dynamic aerodynamic characteristics are very complex because of the asymmetric configuration of war damaged aircraft. In addition to this research, most of the researches focus on the static aerodynamic analysis of battle damage model. Ding[7] conducted an experimental and numerical study to investigate the aerodynamic characteristics of a wingtip-lost transport aircraft in landing mode. This research revealed the pitch-roll coupling effect in static cases. Zhan[8] investigated the consequences of wing damage on a flapping wing micro air vehicle. However, this study also focused on the general lift performance and had not considered the dynamic coupling moment during the flapping motion. Lebeau[9] proposed an experimental-computational investigation of the aerodynamic performance of a damaged UAV wings. This work intended to possible performance thresholds resulting from wing damage. With the development of advanced aircraft technology, if the " injured but not destroyed " aircraft is rescued, it needs to rely more on the dynamic aerodynamic results. Obviously, the current research in this area is still lack, especially the multi-axis coupling problem after the wing surface damage, which has a great impact on the survivability of the war damaged aircraft.

In this paper, based on the previous research, the typical flying wing configuration is taken as the research object, and the damage configuration is established according to the live ammunition strike test, and the concept and identification method of coupling dynamic derivative are deduced by analogy with the conventional dynamic derivative. Using high-precision CFD method, we calculate the static and dynamic aerodynamic characteristics of different damage configurations, and evaluate the influence of damage on the coupling dynamic derivative, which provides support for the flight control of battle-damaged aircraft.

2. Simulation Method

2.1 Damaged Aircraft Model

According to the current live ammunition strike test, the commonly used aircraft damaged models can be determined as two categories: the cutting and local penetration models. The damage of local penetration can be further divided into fragment and discrete rod damages(only different in damage shapes). Moreover, the cutting model is usually reflected in the continuous rod damaged situation with large killing range and overall loss of common components.

In this paper, SACCON flying wing model is used to establish the damaged models, which is one of the standard models for dynamic stability analysis and control system design[10-11]. Figs. 1 and 2 show the two damaged models: the fragment damage and continuous rod damage on SACCON model. Local penetration models can be divided into two categories: one is a single large hole with a radius of 0.4m, and the other is a distributed small hole with a radius of 0.1m. There are two kinds of local cutting damage: wingtip missing and middle wing missing models. The detailed work of the modeling can be referred to my previous research[6].

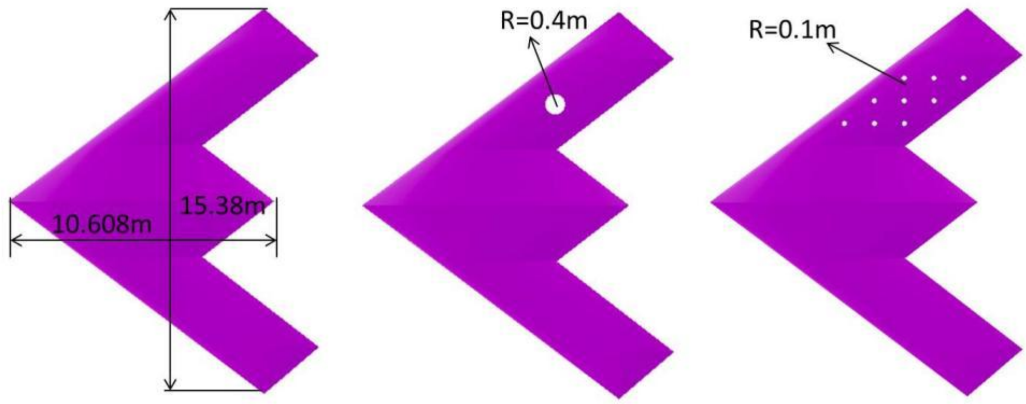


Figure 1 – Fragment damage

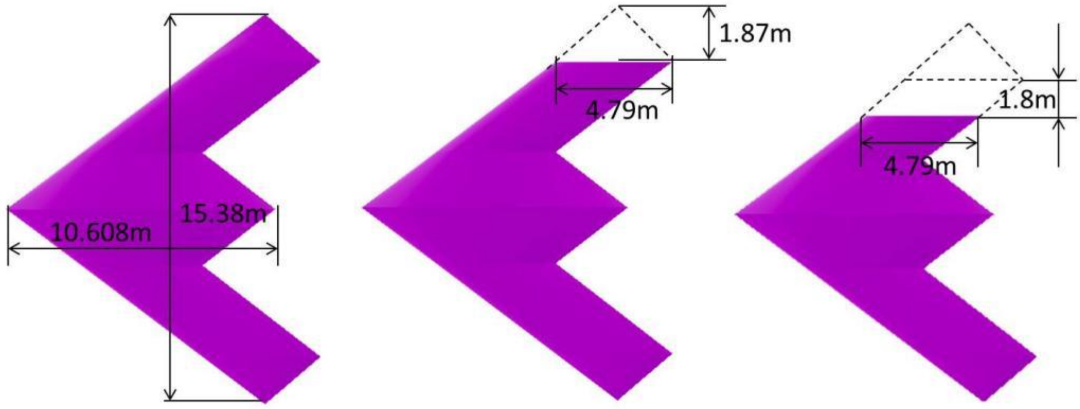


Figure 2 – Continuous rod damage

2.2 Static Aerodynamic Analysis of Damaged Aircraft

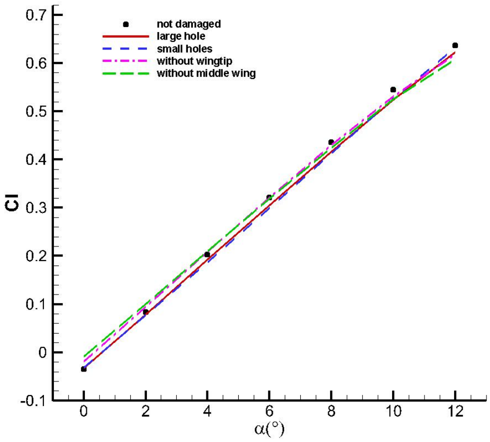
Since large openings are involved in the damaged models with dramatically changing flows (Fig.3), especially for large penetration damage, the relatively stable flow on the wing surface is separated and becomes very unstable so that it is difficult to obtain accurate flow field results by conventional Reynolds average method. Hence, the SA-DES model[12] is used to solve the static and dynamic flow fields of the damage configuration in this study, which provides more accurate aerodynamic data for the subsequent analysis of dynamic derivatives. The SA-DES model equation can be expressed as:

$$\frac{\partial}{\partial t}\left(\rho\tilde{v}\right)+\frac{\partial}{\partial x_i}\left(\rho\tilde{v}u_i\right)=G_v+\frac{1}{\sigma_{\tilde{v}}}\left[\frac{\partial}{\partial x_j}\left\{(\mu+\rho\tilde{v})\frac{\partial\tilde{v}}{\partial x_j}\right\}+C_{b2}\rho\left(\frac{\partial\tilde{v}}{\partial x_j}\right)^2\right]-Y_v+S_{\tilde{v}}$$

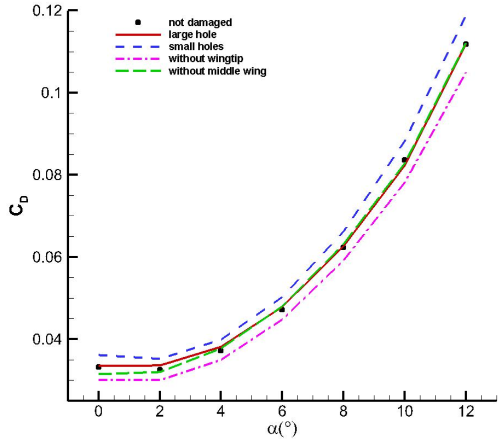
$$G_v=C_{b1}\rho\tilde{S}\tilde{v}\,,\ \tilde{S}\equiv S+\frac{\tilde{v}}{\kappa^2\tilde{d}^2}f_{v2}\,,\ Y_v=C_{w1}\rho f_w\left(\frac{\tilde{v}}{\tilde{d}}\right)^2,\ r\equiv\frac{\tilde{v}}{\tilde{S}\kappa^2\tilde{d}^2}\,, \tag{1}$$

$$\tilde{d}=\min(d,C_{des}\Delta_{\max})$$

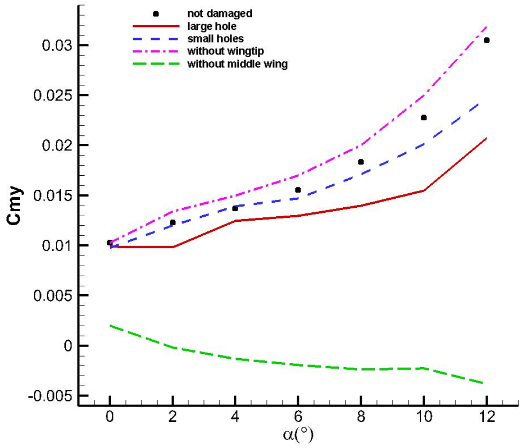
The static aerodynamic force of damaged and non-destructive configuration is calculated firstly by using this method. The calculation results are shown in Fig. 3-4. Compared with the aerodynamic results of the four cases, the lift coefficient is relatively close, but the reference area changes due to the defect area. When the angle of attack is relatively large, the lift coefficient decreases slightly; The resistance coefficient is related to the damage location. The separated vortex formed by the distributed damage holes results in the increase of friction resistance and differential pressure resistance. However, the wetted area decreases after the damage of the middle wing. The influence range of the tip eddy current extends to the inner wing, so that the resistance is higher than that of the tip damage configuration; The pitching moment coefficient is related to the lift loss before and after the reference point. For example, the area loss in front of the reference point of the large hole penetration model, which increases the bow moment, while the damage of the middle wing results in more lift loss in front, which also generates bow moment; An asymmetric profile produces a rolling moment. After the damage of the right wing, the lift decreases, so the coupling roll moment is generated, which increases with the increase of the effective lift area.



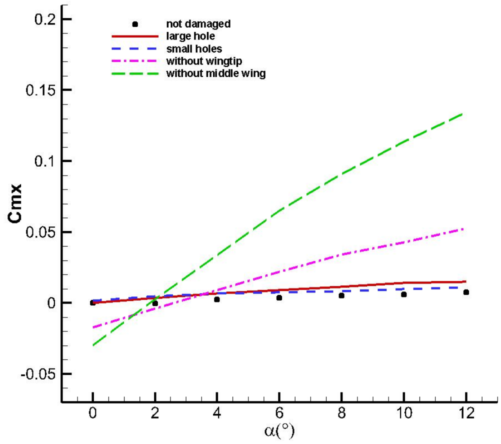
(a) The lift coefficient



(b) The drag coefficient



(c) The pitching moment coefficient



(d) The rolling moment coefficient

Figure 3 – Static aerodynamic calculation results.

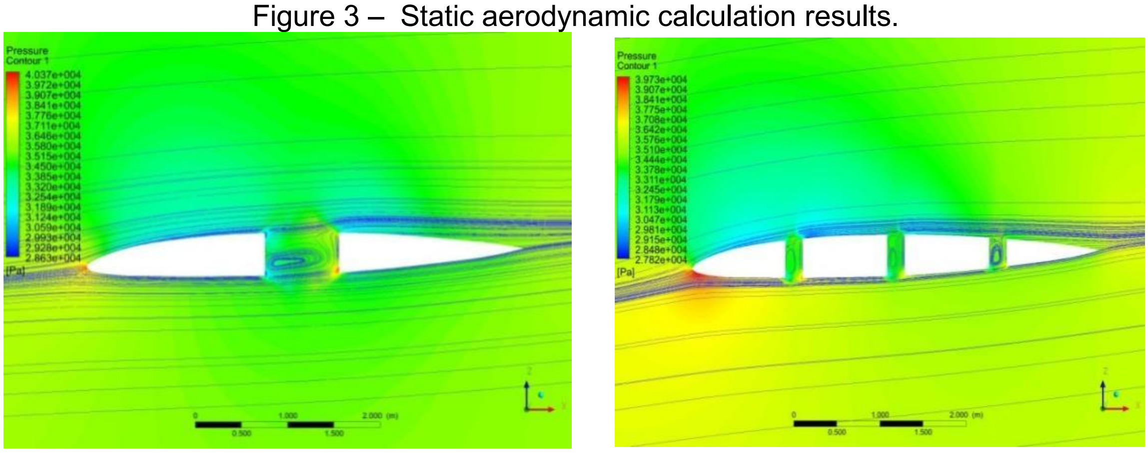


Figure 4 – Separation flow of large hole damaged model

3. Calculating Method and Influence Mechanism of Coupled Dynamic Derivative Caused by Aircraft Local Damage

3.1 Calculating Method of Coupled Dynamic Derivative

The conventional dynamic derivative is obtained by Taylor expansion of the motion parameters by unsteady aerodynamic forces:

$$C_i(t) = C_i(\alpha, \beta, \dot{\alpha}, \dot{\beta}, p, q, r) \tag{2}$$

where C_i is the longitudinal and lateral direction aerodynamic forces and moments.

The mathematical model to describe the unsteady aerodynamics with dynamic derivatives decouples the longitudinal and lateral characteristics of the aircraft. Then:

Longitudinal: $C_m(t) = C_m(\alpha, \dot{\alpha}, q)$

Lateral direction: $C_{l,n}(t) = C_{l,n}(\beta, \dot{\beta}, p, r)$

The dynamic derivatives of longitudinal and lateral directional obtained by the conventional technologies constitute the basis of the flight quality analysis of conventional aircraft. However, this statement is not completely reasonable for the damaged aircraft. The asymmetric damage form causes the asymmetry of aerodynamics, which is completely different from the asymmetric vortex breakdown effect on the conventional symmetric aircraft at large angle of attack. Therefore, the coupling dynamic derivative caused by structural damage will be generated, which is most obviously reflected in the lateral-directional disturbance caused by longitudinal motion and the pitching disturbance caused by lateral-directional motion.

Taking the longitudinal motion as an example, the coupled rolling moment and yaw moment can be described as (expressed uniformly by C_i):

$$C_i = C_{i0} + C_{i\alpha}\Delta\alpha + C_{i\dot{\alpha}}\Delta\hat{\dot{\alpha}} + C_{iq}\hat{q} + C_{i\dot{q}}\hat{\dot{q}} + \hat{\Delta}(\Delta\alpha, q) = C_{i0} + C_{i\alpha}\Delta\alpha + (C_{i\dot{\alpha}} + C_{iq})\hat{q} + C_{i\dot{q}}\hat{\dot{q}} + \hat{\Delta}(\Delta\alpha, q) \tag{3}$$

The corresponding produced coupling derivative is denoted as $C_{i\dot{\alpha}} + C_{iq}$. This parameter shows that the damaged aircraft has coupling dynamic stability performance, which is different from the conventional no-damaged configuration. The coupling derivatives are the key factors affecting the flight quality of damaged aircraft.

Similarly, when the lateral rolling motion occurs, the configuration damage asymmetry will also produce the "lateral-longitudinal" coupling phenomenon. That is to say, when rolling laterally, the pitching moment coefficient in longitudinal direction is produced.

Taking the lateral rolling motion as an example, the coupled pitching moment can be described as:

$$C_m = C_{m0} + C_{m\beta}\Delta\beta + C_{m\dot{\beta}}\Delta\hat{\dot{\beta}} + C_{mp}\dot{p} + C_{m\dot{p}}\hat{\dot{p}} + \hat{\Delta}(\Delta\beta, p) \tag{4}$$

where C_{mp} represents the coupling dynamic derivative of rolling effect on longitudinal direction. The value of the conventional configuration is almost zero, but when one side of the structure is lost because of war damage, the local aerodynamic force of the component changes. When rolling forward, the local angle of attack of the right wing increases, while the additional angle of attack of the left wing decreases. With the increase of angle of attack, the increase of lift coefficient of the damaged wing is less than that of the original wing, and the aerodynamic force distribution along the chord direction changes, as shown in Fig. 5, which leads to the difference of the pitching moment around the reference point, resulting in the additional coupled longitudinal dynamic derivative. On the one hand, the lift of the defect disappears, on the other hand, there is local damage, which makes the local resistance increase. In addition, the results show that the change of local resistance varies with different damage forms.

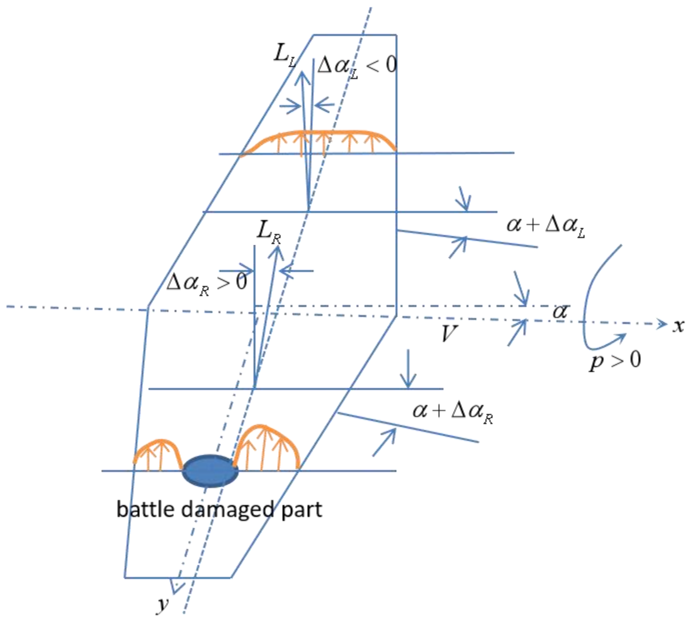
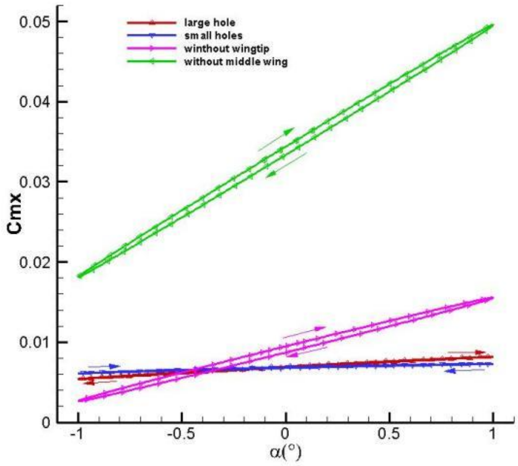


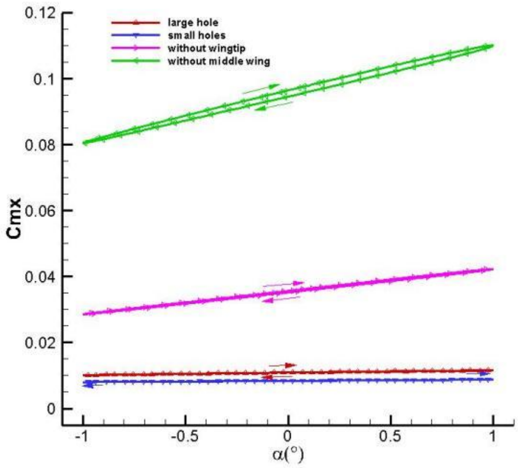
Figure 5 – "Lateral-longitudinal" aerodynamic coupling effect of damage configuration

3.2 Simulation Analysis on Coupling Effect of Longitudinal Motion to Lateral Aerodynamics

The rigid dynamic grid technique[13] is used to simulate the motion of aircraft. By forcing the aircraft oscillating around its center of gravity with simple harmonic motion, the dynamic motion is expressed as $\alpha = \alpha_0 + \alpha_m \sin(\omega t) = \alpha_0 + 1^\circ \sin(3.8594t)$. The calculation status is Ma=0.6 （H=6Km）.The corresponding reduction frequency is $k = \omega c / 2V_\infty = 0.05$ .The calculated pitch-roll moment coefficient is shown in Fig. 6. As shown in Fig.7, The cross dynamic derivative $C_{i\dot{\alpha}} + C_{iq}$ is identified by least square method.



（a） α_0=4°



（b） α_0=8°

Figure 6 – Unsteady rolling moment coefficient caused by the pitching oscillation.

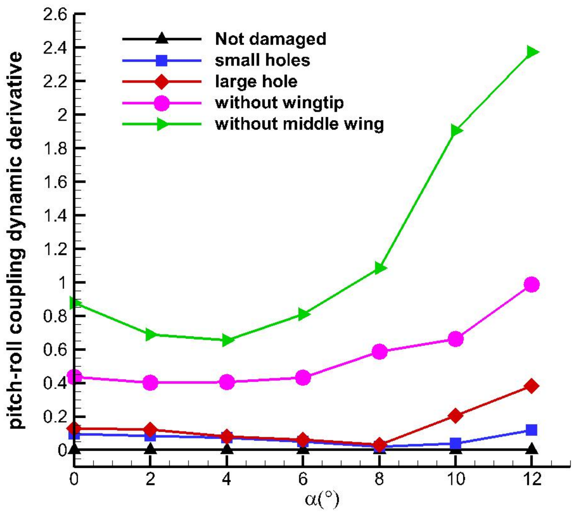


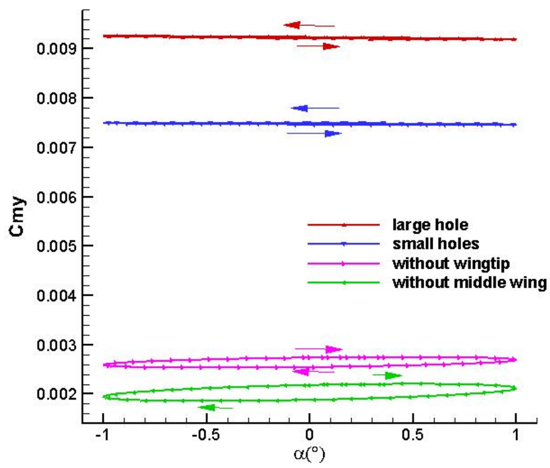
Figure 7 – "Longitudinal-lateral" coupling dynamic derivative

The hysteresis loop curve of pitch-roll cross moment coefficient shows that if the hysteresis loop of coupled roll moment coefficient is clockwise, the corresponding dynamic derivative value should be positive. This shows that after the right wing is damaged, the pitching harmonic motion induces the lateral negative damping effect. With the increase of the damage area, the hysteresis area increases, which indicates that the coupling effect becomes more obvious. The dynamic derivative identification of $C_{i\dot{\alpha}} + C_{iq}$ results show that with the increase of angle of attack, the positive dynamic derivative first decreases and then increases. The larger the missing area is, the larger the coupling dynamic derivative value is. The results show that for battle damage configuration, although the aerodynamic asymmetry leads to the "longitudinal-lateral" coupling dynamic derivative. However, in a certain range of attack angle, there is a small relative dynamic derivative, which is related to the flow field distribution in the process of attack angle change. The value can be used to reconstruct the manipulation strategy.

3.3 Simulation Analysis on Coupling Effect of Lateral Motion to Longitudinal Aerodynamics

Similarly, the rigid dynamic mesh technique is also used to drive the lossless and damaged configurations for sinusoidal rolling motion. The motion is $\phi = \phi_m \sin(\omega t) = 1^\circ \sin(1.20156t)$.

The corresponding reduction frequency is $k = \omega b / 2V_\infty = 0.05$ .The calculated roll-pitch moment coefficient is shown in Fig.8. As shown in Fig.9, The "roll-pitch" cross dynamic derivative C_{np} is identified by least square method.



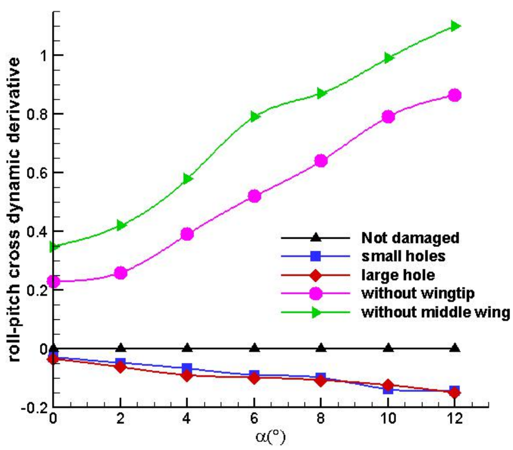


Figure 8 – Unsteady pitching moment

Figure 9 – "Roll-pitch" cross dynamic derivative coefficient caused by the rolling motion. ($\alpha_0 = 0^{\circ}$)

There is a loss of lift area because of the asymmetry of the structure after the battle damage. When the aircraft rolls laterally, the aerodynamic force distribution of the left and right wings will also change. This change results in the change of lift distribution before and after the chord moment reference point / center of gravity, which changes the pitching moment characteristics and causes cross coupling characteristics. In contrast, the hidden lateral to longitudinal coupling characteristics may not be very obvious. But for the configuration in this paper, with the increase of battle damage area, it is obvious that the hysteresis area of cross moment is also increasing. As shown in Fig.8, in the local penetration damage configuration caused by discrete rod warhead, although the lift surface is missing, the overall wing profile does not change. The aerodynamic changes are more reflected near the local damage location, so the corresponding hysteresis area is smaller. From the surround direction of hysteresis, the cross moment of "roll -pitch" of discrete rod damage is counterclockwise, showing a positive damping effect. With the increase of attack angle, the separation of local flow field increases, and the effect on global flow field becomes stronger. At this time, the surround direction of hysteresis remains unchanged, and the area increases, which shows the increase of absolute value of negative dynamic derivative. However, the value of the cross coupling derivative is relatively small generally.

For the whole cutting damage caused by continuous rod warhead, the change of aerodynamic force is relatively obvious. The cross moment hysteresis of the two damage configurations is clockwise, which play a negative damping role. At this time, the decrease of the spanwise dimension changes the position of the wing tip, so the aerodynamic force of the damaged side will change along the chord direction. With the increase of the angle of attack, the cross coupling dynamic derivative increases, and the magnitude is relatively large, which can not be ignored.

4. Conclusions

This paper develops two types of damage models of local penetration and global cutting for SACCON flying wing configuration, and deduces the definition and identification method of coupled dynamic derivative for local-damaged configuration. The high-precision SA-DES model is used to simulate the static and dynamic aerodynamics of each damaged model, and various coupled dynamic derivatives of the damage configurations are identified, and the variation relationship between the damage and the characteristics of the coupled dynamic derivatives is expounded.

(1) The cross dynamic aerodynamic force of damaged aircraft is different from that of conventional aircraft. At a very small angle of attack, there will be cross coupling moment because of the configuration asymmetry;

(2) In the case of longitudinal disturbance, the "Longitudinal-lateral" coupling cross moment hysteresis is positive in both continuous and discrete rod damage configurations, showing negative damping in the circumferential direction, and the corresponding dynamic derivative is positive. With the increase of the angle of attack, the dynamic derivative first decreases and then increases, indicating that there is an interval conducive to reconstruct the manipulation strategy;

(3) In the case of lateral disturbance, the longitudinal coupling moment hysteresis is related to the damage form. The damage of discrete rod presents strong local characteristics, but does not change the whole structure significantly, so that the relative coupling characteristics are weak. Moreover, the "Lateral-longitudinal" coupling moment is counterclockwise, and the corresponding dynamic derivative is negative. However, the damage of the continuous rod leads to the overall loss of components, which seriously affects the aerodynamic change and changes the distribution along the chord. The cross coupling dynamic derivative is positive, and the magnitude is relatively large. With the increase of attack angle, the absolute values of these coupling dynamic derivatives increase, which reflects the enhancement of coupling effect caused by component defect.

This study further clarifies the influence of combat damage on the dynamic stability of aircraft, which is of great significance to the reconfiguration control strategy of damaged aircraft and the improvement of survivability. However, the research on damage types and dynamic aerodynamic coupling characteristics of combat damaged aircraft is still very rough. Future work will focus on the multi-axis coupling characteristics of complex damaged shape and accuracy of modeling.

5. Acknowledgements

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7. Copyright Statement

References

[1] Rasuo B. Damage tolerance and survivability of composite aircraft structures[J]. *Structural Integrity and Durability of Advanced Composites*, 2015:641-657.

[2] Pei Y, Cheng T, Xie M. Assessing survivability for damaged aircraft in the combat environment[R]. *2014 IEEE International Conference on Industrial Engineering and Engineering Management*, 2014.

[3] Connelly J, Gatto J . Increasing aircraft survivability through explosives detection[C]. *Aircraft Engineering, Technology, & Operations Congress*. 2013.

[4] Figat M, Kwiek A. Aerodynamic and static stability investigation into aircraft coupled system to suborbital space flights[J]. *Aircraft Engineering and Aerospace Technology*, 2021(ahead-of-print).

[5] Sanchez-Laulhe E, Fernandez-Feria R, Acosta J A. Effects of Unsteady Aerodynamics on Gliding Stability of a Bio-Inspired UAV[C]. *2020 International Conference on Unmanned Aircraft Systems*, 2020.

[6] Mi B G. Simulation on the dynamic stability derivatives of battle-structure-damaged aircrafts[J]. *Defence Technology*, 2021, 17(3):987-1001.

[7] Ding M, Zeng C, Binienda W K. Assessment on aerodynamic degradation for wing-damaged transport aircraft[J]. *Aircraft Engineering and Aerospace Technology*, 2020, 92(7):973-979.

[8] Zhan T, Fan F, Liu L, et al. Flying With Damaged Wings: The Effect on Flight Capacity and Bio-Inspired Coping Strategies of a Flapping Wing Robot[J]. *IEEE Robotics and Automation Letters*, 2021, 6(2): 2114-2121.

[9] Lebeau R P, Gururajan S, Lensing T , et al. An Experimental-Computational Investigation of the Aerodynamics of Damaged UAV Wings[C]. *AIAA Scitech 2020 Forum*. 2020.

[10] Williams D R, Seidel J, Osteroos R, et al. NATO AVT-239 Task Group: Flight Control Derivatives using Active Flow Control Effectors on the ICE/SACCON UAS Model[C]. *AIAA Scitech 2019 Forum*. 2019.

[11] Roy J, Morgand S. SACCON CFD Static and Dynamic Derivatives Using elsA[C]. *AIAA Applied Aerodynamics Conference*. 2013.

[12] Morton S A, Cummings R M, Kholodar D B. High Resolution Turbulence Treatment of F/A-18 Tail Buffet[J]. *Journal of Aircraft*, 2004, 44(6):1769-1775.

[13] Hwang C J, Yang S Y. Inviscid analysis of transonic oscillating cascade flows using a dynamic mesh algorithm[J]. *Journal of Propulsion and Power*, 2015, 11(3):433-440.