THE SIMULATION AND FLIGHT VERIFICATION OF ACTIVE AEROELASTIC CONTROL

***Liu Yi*[1], *Yuan kaihua*[1], *Ciao Xiaolong*[1], *Jin Yi*[2] *and Meng yang*[3]**

1,Institute of Beijing Mechanics and Electronics /Fengtai District, Beijing, China
2,Guangdong BODA Electronic Technology Co., Ltd, Guangdong, China
3, Beihang University, Beijing,China

In this paper, an active aeroelastic control verification flight platform based on intelligent sensing is presented. The flight platform design concept is illustrated including key performance parameter, the aerodynamic layout and structure configuration. Detailed simulations in aerodynamics, structural dynamics and active aeroelastic control are conducted to ensure the safety and effective verification of the flight platform. Finally, a basic fight test for gust alleviation by active aeroelastic control is executed. The flight test result demonstrate that the wing tip vibration response is reduced by more than 30% via active aeroelastic control system, and the load envelope is increased by 12%. At the same time, the reliability and technical maturity of the active aeroelastic control system are verified, which lays the technical foundation for the further improvement of the test speed and the active control effect.

Keywords: Active Aeroelastic Control, flight platform, flight test.

1 Introduction

Aeroelasticity is a subject that studies the mechanical behavior of elastic aircraft such as missiles and aircrafts in the flow. The aircrafts may induce static and dynamic response because of the interaction between aerodynamics and structures, and those elastic deformations will also affect the aerodynamic force, inertial force and elastic force, this interaction of aerodynamic force, inertial force, which is called aeroelastic effect that often affects the flying quality, performance and safety of aircrafts[1].

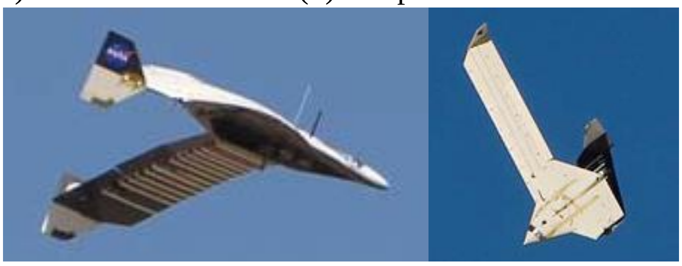
With the development trends towards flexibility, lightweight structure and high maneuverability of aircraft design, the advanced aerodynamic layout and new structural materials are used and Thus elastic deformation of wings under the aerodynamic loads is inevitable. the aeroelastic problems of flexible aircrafts are becoming more and more complex, and many new problems occur[2].

Rigid-elastic coupling problem: when the frequency of rigid body is close to the frequency of structural elastic vibration, the couple rigid-elastic vibration will occur and become unstable, which is called body-freedom flutter. The mishap of “Helios” is the typical rigid-elastic coupling problem. The accident analysis report suggests that coupling effects should be analyzed considering the nonlinearity in time domain[3]. X-56a also suffered from the body-freedom flutter.

Nonlinear problem: the nonlinear problem is always the hot spot of aeroelastic research. The nonlinear coupling among shock wave separation, dead zone of actuator and structural vibration make the B-2 bomber encountered aircraft pitch oscillation in low altitude and high speed flight test[4].

Gust response problem: the gust disturbance in flight will directly affect the structure strength and worsen the flight quality. gust response and alleviation also becomes a key problem in future aircraft design[5].

(a) Helios (b) the pitch oscillation of B-2



(c) X-56a

Fig. 1. Some typical new problems of aeroelastocity[6]

In conventional aircraft design, aeroelastic effects are usually modified by stiffening the wings or adding additional control surfaces, but it will bring weight cost and further reduce the overall performance of the aircraft. The traditional aircraft design concept is no longer suitable for modern aircraft design[789]. The technology of active aeroelastic control[10] can effectively solve the problem that traditional design hard to overcome. It adopts the design idea of making full use of the structural deformation instead of avoiding it. It can change the airflow distribution and structural modal characteristics of the wing surface by making active and reasonable use of the deformation of the wing surface intelligently according to the current flight environment and response characteristics of the aircraft[11,12,13,14]. These active aeroelastic control methods [9]will improve the maneuverability, increase the flutter critical velocity and alleviate gust response of the aircraft in the disturbed environment. On the other hand, the optimal aerodynamic performance is achieved by adaptive deformation under various flight conditions, to reduce aerodynamic drag and aircraft structure weight.

In this paper, considering the aeroelastic characteristics of flexible aircraft, a flight verification platform is designed with advanced active aeroelastic control design concept, which makes the deflections from “passive defense” into “active use”[16]. A flight test is conducted to help to verify the active aeroelastic control method in gust alleviation and explore for the further application and intelligentization of active aeroelastic control technology.

2 Design for Flight Platform

2.1 Overall Layout Design

The designed speed of the active aeroelastic control flight platform is 250 km/h. modular assembly with a certain load expansion capacity is adopted, which can support other aeroelastic technology validation. The main performance parameters of the active aeroelastic control flight platform are shown in the table below.

Table 1. Flight platform parameter

parameter	value
Maximum flight speed	250km/h
Minimum flight speed	80km/h
Maximum overload capability	2.5g
Load capacity	2kg
Maximum endurance	45min
Take-off weight	17kg
Wing span	4.5m
Aspect ratio	15.5
Fuselage length	2.2m
Span of v-tail	0.8m

The flight platform adopts the conventional aerodynamic layout: the high aspect ratio straight wing with single beam structural configuration, a v-shaped tail to reduce the structural weight and reduce the aerodynamic drag. The whole body is streamlined to achieve drag reduction. A internal jet engine is used as the power to increase the flight speed of the aircraft.

Fig. 2. The layout for flight platform

2.2 Aerodynamic Evaluation

Aerodynamic characteristics of the flight platform is evaluated by Fluent software. the air state equation is considered as an ideal gas, the air viscosity coefficient is modified by Sutherland formula, the turbulence model is the standard k-e model. Mixed Unstructured mesh are used for the surface and spatial calculation of the model. The surface mesh is shown below. The referenced length is 0.2m,and the referenced area is 0.9m^2.

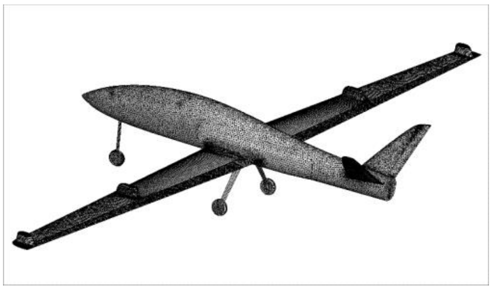
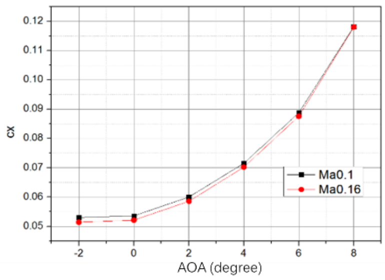
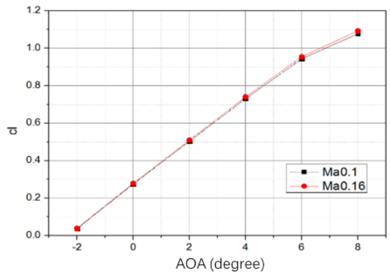


Fig. 3. The surface mesh

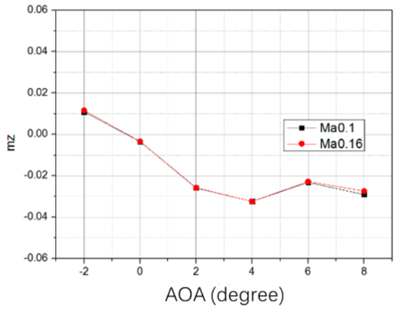
The calculated aerodynamic results are presented below.



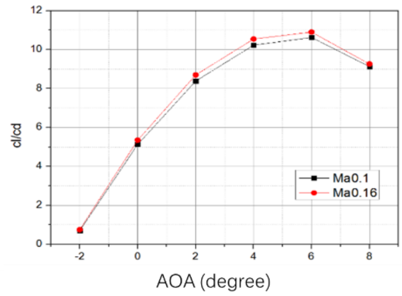
(a) drag



(b) lift



(c) pitch moment



(d) lift-drag ratio

Fig. 4. Aerodynamic charateristcs

From the curves of aerodynamic coefficients with the angle of attack(AOA), it can be seen that the aircraft is longitudinal statically stable and has a high stability margin at the positive angle of attack, small static instability exists at the negative angle of attack. The lift coefficient is linear before 8 °AOA, when the angle of attack is greater 8 °AOA, the nonlinear characteristic is enhanced. The lift-drag ratio is largest when the angle of attack is 4 °.

2.3 Structure Design

A double-tube-beam composite wing is adopted, which can meet the strength requirements and reduce the stiffness as much as possible. PMI foam is used to maintain the shape of leading edge. Glass fiber is used as wing skin material. Three sets of rudder surfaces are designed for rolling control and wing vibration suppression. The structural FEM model is presented below.

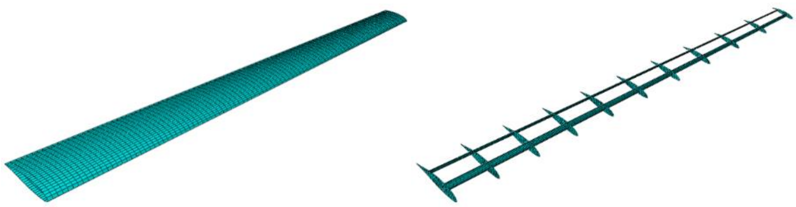


Fig. 5. FEM model of wing

The strength and deflection of the wing under 2.0g overload are evaluated. The wing skin stress cloud is shown in the following figure. The maximum tensile and compressive stresses on both upper and lower surfaces are less than 100MPa, which is far small than the strength of glass fiber. When loading the wing with a load of 2.0 g, the wing deflection is shown in the following figure. The maximum deflection of the wingtip region is 600mm, which indicates that the wing has relatively large flexibility and meets requirements for aeroelastic characteristic research.

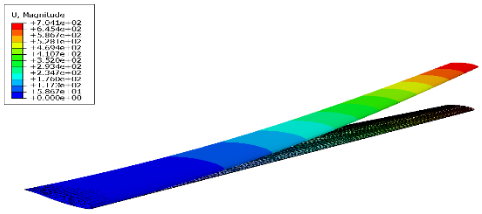


Fig. 6. Deflection of wing

3 Simulations

The structural FEM model is shown below.The linkage between rudder and stabilizer is simulated by spring element, so that the vibration characteristics of the whole machine can be accurately simulated. Unsteady aerodynamic modeling of the aircraft, including the wing, fuselage and tail of the three parts of the model, as shown in the following diagram. The wing and tail element are characterized by plane grid of wing surface and body grid of fuselage.

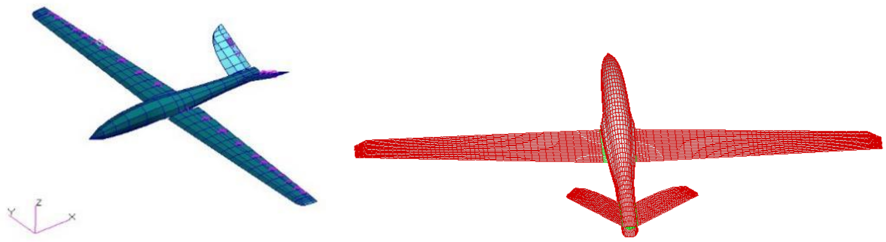
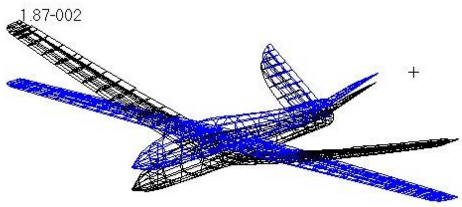
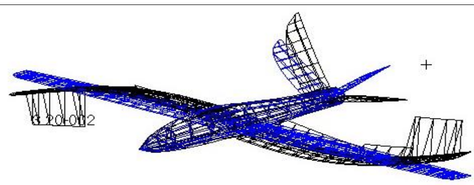
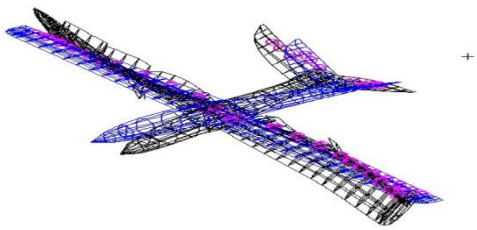
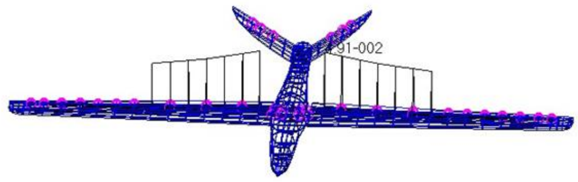
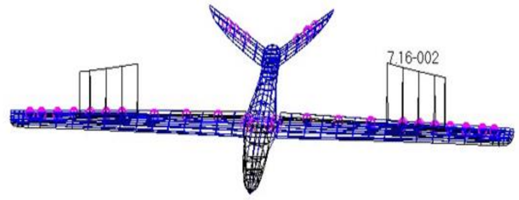


Fig. 7. FEM model and aerodynamic model

The main structural dynamic modal is listed here:

Modal name	frequency Hz	Modal shape
Wing symmetric bend	3.69	
Wing antisymmetric bend	7.20	
Wing twist	20.34	

Inside Aileron rotation	13.52	
Middle Aileron rotation	16.15	
Outside Aileron rotation	18.22	

The open-loop response characteristics of an aircraft are analyzed. Under gust disturbance, the maximum response peak of the bending moment of the wing root section is located at the frequency of the symmetric first bend of the wing.

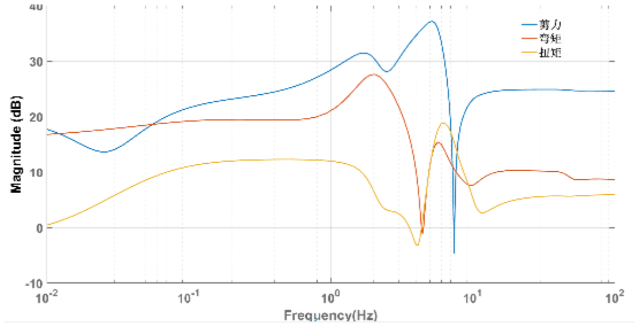


Fig. 8. open-loop response discrete gust disturbance

Both the middle aileron control surface and the outer aileron control surface are used as the control inputs to reduce the maximum deflection angle. The feedback signal is composed of barycenter normal acceleration, left wing tip normal acceleration and right wing tip normal acceleration. Thus an active aeroelastic control system for gust response alleviation is designed. A gust velocity and gust acceleration disturbance is given as inputs, the resultant wing root shear, bending, and torque simulation are shown below. The control input rudder surface deflection angle is also presented. It can be seen from the figure that the peak moment of the root bending moment of the wing is reduced by 43.2% and the maximum moment of the root torsion moment is reduced by 64.9%. The maximum deflection angle of the outer aileron with control is less than 13°, and that of the other control surfaces is less than 7°. The designed gust load alleviation control system well satisfy the requirements.

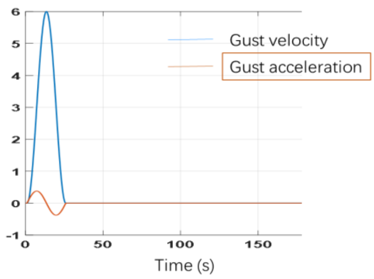


Fig. 9. Gust disturbance

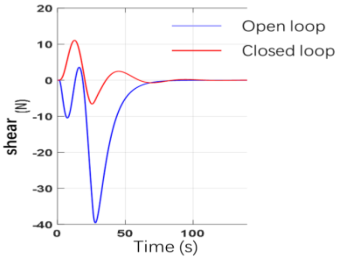


Fig. 10. Wing root shear

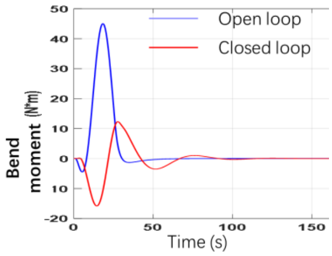


Fig. 11. Wing root bending moment

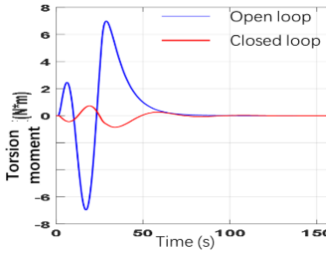


Fig. 12. Wing root torsion moment

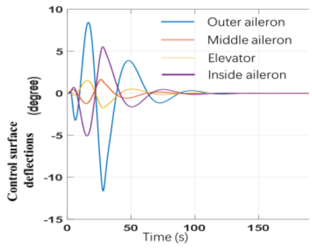


Fig. 13. Control surface deflections

4 Flight Test

Here a basic flight test is conducted to verify the flight platform and the effectiveness of active aeroelastic control system. The flight platform is shown below. The fuselage is loaded with engine control module, flight autopilot module, active aeroelastic control module, 360-degree video camera and LED wingtip position indicator. During the flight test, the autopilot flight is realized to plan the flight path and make the route, and the active aeroelastic control system is opened when the plane reaches the standard test section, flight verification of the effectiveness of active aeroelastic control of gust mitigation was carried out.

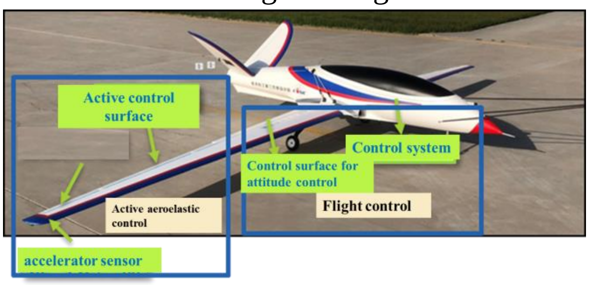
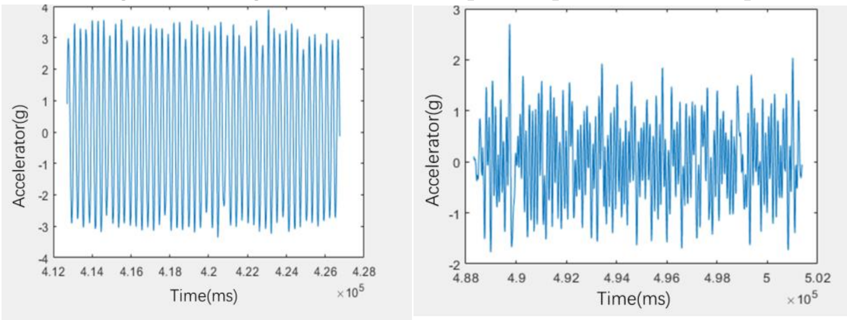


Fig. 14. Functions composition of flight platform

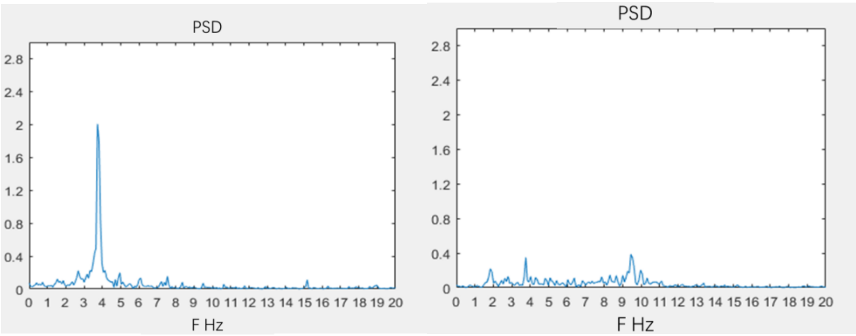
The wing deformation in a disturbed environment is both open loop and closed loop of active aeroelastic control system is shown below. In the open-loop the maximum deformation of the wing tip under gust disturbance is about 15% of the half-wing-span. When the active control system is turned on, the maximum deformation of the wing tip decreases to about 5% of the half-wing-span in the closed-loop state. So the active aeroelastic control effect is remarkable. For wing tip acceleration response, the vibration amplitude in closed loop decreases significantly, and the average vibration amplitude decreases more than 30% . When the active aeroelastic control system was not switched on, the amplitude of wing tip acceleration vibration was about 6.5 g, and when the active aeroelastic control system was switched on, the peak value of wing tip acceleration vibration decreased to 4.3 g, the peak value of the active aeroelastic control gust is reduced by 33% , which can satisfy the request that the amplitude of the wing tip acceleration is reduced by more than 20%.

Fig. 15. Wing deformation in open loop and closed loop



Open loop b. Closed loop

Fig. 16. Wing tip accelerator response in time domain



a. Open loop b. Closed loop

Fig. 17. Wing tip accelerator response in frequency domain

This flight test verified the effectiveness of the active aeroelastic control system at high speed (over 200km/h). In the gust disturbance environment, the wing tip vibration response is reduced by more than 30% , and the load envelope is increased by 12% . At the same time, the reliability and technical maturity of the active aeroelastic control system are verified, which lays the technical foundation for the further improvement of the test speed and the active control effect.

5 conclusion

In this paper, an active aeroelastic control verification flight platform based on intelligent sensing is presented. The flight platform design concept is illustrated including key performance parameter, the aerodynamic layout and structure configuration. For further intelligent perception- intelligent sensing-intelligent active control system foundation, radar wind fields measurement and distributed FGB strain sensor is introduced and equipped on the flight platform. Detailed simulations in aerodynamics, structural dynamics and active aeroelastic control are conducted to ensure the safety and effective verification of the flight platform. Finally, a basic fight test for gust alleviation by active aeroelastic control is executed. The flight test result demonstrate that the wing tip vibration response is reduced by more than 30% via active aeroelastic control system, and the load envelope is increased by 12%. At the same time, the reliability and technical maturity of the active aeroelastic control system are verified, which lays the technical foundation for the further improvement of the test speed and the active control effect.

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