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AEROELASTIC RESPONSE SIMULATION FOR DIFFERENT EXCITATION TECHNIQUES IN FLIGHT FLUTTER TEST OF MODERN CIVIL

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Abstract

In flight test, different kinds of excitations (Control Surface Pulses, Oscillating Control Surfaces, Thrusters, Inertial Exciters, Aerodynamic Vanes, Dynamic Engineering Incorporated (DEI) rotating cylinder exciters, Random Atmospheric Turbulence) are used to excite the aircraft structure. To improve the flight flutter test safety and schedule, the flight flutter testing and response simulation for different kinds of excitation techniques is needed to study. The structure vibration response and stability characteristics in flight flutter test point can be obtained by aeroelastic response simulation technique under different kinds of excitations. Quantities of parameters needed in real-time stability monitoring are also obtained, and the excitation force level and response amplitude in real-time test can also be estimated.

This paper reviews the characteristics and requirements of flight flutter test, and presents the flight flutter testing and response simulation technique under different kinds of excitations. The present method is described from four aspects: the dynamic finite element modeling of the airplane configuration for flight flutter test, frequency domain and time domain response simulation modeling, response simulation under different kinds of excitations, and the aeroelastic stability examination. Simulation models of four kinds of excitations are built, i.e. the Control Surface Pulses and Oscillating excitation, Inertial Exciters excitation and Random Atmospheric Turbulence.

Aeroelastic response under flight flutter test excitations is studied in four numerical test cases: the first application is the 15-deg sweptback wing under an impulsively applied load at the wing tip in order to investigate the transient response at subcritical, critical, and supercritical speeds, and the flutter stability examination is presented. The second application uses a transport airplane aileron excitation response simulation to examine the flutter stability. The third application uses a transport airplane aileron excitation response simulation results in comparison with flight flutter test results, the result agrees well with each other. The fourth application uses a transport airplane model that conducts the Control Surface Pulses excitation, Oscillating Control Surfaces excitation, Inertial Exciters excitation and Random Atmospheric Turbulence excitation techniques in aeroelastic response simulation, and the result is analyzed. These four example application demonstrate that the response simulation technical under the excitation of flight flutter test is valid and feasible in engineering. Finally, comments regarding the direction of future research are presented in response simulation technique with flight flutter test excitation.

1 Introduction

Modern high-performance civil aircraft use thin, low-drag supercritical airfoils designed for maximum aerodynamic efficiency, and the cruise speed becomes faster and faster[1]. The flutter boundary is nearly equal to the sound speed boundary. For example, the Boeing civil airplanes' flutter flight test velocity boundary is Mach 0.89 for B737 and increases to Mach 0.91 for B767, and Mach 0.95 for the up to date advanced B787. In addition, the use of high gain, digital flight control systems can result in an adverse interaction with the aircraft structural modes and cause aeroservoelastic (ASE) unstable[2]. Once the airplane flutter occurs in flight, the airplane would change from a stable safe state to another instable unsafe sate in approximately three seconds, the dynamic loads and stress would damage structure, resulting in flight accident[3].

Flight flutter (including aeroservoelasticity) test is the final verification for the aeroelastic stability of new type of aircraft designs and for modifications of existing vehicles in the desired flight envelope. The Airworthiness Standards: Transport Category Airplanes such as CCAR25.629, FAR25.629, CS 25.629 define the requirements for flight flutter test.

Modern civil aircraft must be designed according to the requirements of transport category airplanes. Many new requirements and challenges are represented for flight flutter test in modern high-performance civil aircraft design and project. For example, the flutter boundary is quite close to the sound speed boundary, and the risk level for flight flutter test becomes much higher, while the project periods of flight flutter test is restricted.

Airworthiness regulations 25.629(e) require that stability though out the required flight regime should be demonstrated by tests of the actual flying aircraft, commonly termed flight flutter tests. Flight flutter test consist of flying an aircraft at a range of subcritical air speed while applying some form of excitation to the structure. The aeroelastic response of the aircraft is recorded at a number of measurement stations, and the data is curve fitted to determine the stability at the current flight speed and predict whether it is safe to proceed to the next test point.

In flight flutter test, the level flight and dive flight are conducted to achieve the maximal velocity and Mach number at V_{DF}/M_{DF} flight envelop. In flight test, different kinds of excitations (Control Surface Pulses, Oscillating Control Surfaces, Thrusters, Inertial Exciters, Aerodynamic Vanes, Dynamic Engineering Incorporated (DEI) rotating cylinder exciters, Random Atmospheric Turbulence) are used to excite the aircraft structure. The critical flutter mode response is recorded, then damping and frequency characteristics are analyzed. The aeroelastic stability of the vehicle is examined by the trend of vibration accelerometer response data, damping and Power Spectral Density (PSD) [4-7].

To improve the flight flutter test safety and schedule, the flight flutter testing and response simulation for different kinds of excitation techniques is needed to study. The structure vibration response and stability characteristics in flight flutter test point can be obtained by aeroelastic response simulation technique under different kinds of excitations. Quantities of parameters needed in real-time stability monitoring are also obtained, and the excitation force level and response amplitude in real-time test can also be estimated.

This paper reviews the characteristics and requirements of flight flutter test, and presents the flight flutter testing and response simulation technique under different kinds of excitations. The present method is described from four aspects: the dynamic finite element modeling of the airplane configuration for flight flutter test, frequency domain and time domain response simulation modeling, response simulation under different kinds of excitations, and the aeroelastic stability examination. Simulation models of four kinds of excitations are built, i.e. the Control Surface Pulses and Oscillating excitation, Inertial Exciters excitation and Random Atmospheric Turbulence.

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2 Characteristics Of Flight Flutter Test

Because flight flutter test is the only MOC6 Flight test items in before Type Inspection Authorizations (TIA), Flutter testing is critical to any aircraft development, safety, process and cost program.

Flight flutter testing is to verify the aeroelastic stability(flight flutter testing) and aeroservoelastic stability(ASE testing) in condition of high speed refer to agreement 25.629/23.629 in Transport airplane Airworthiness Standards, with stall spin and air parking to be recognized as the three most dangerous subjects. The flight envelope is expanded from V_{MO}/M_{MO} to V_{DF}/M_{DF} in Flight flutter testing. Clearance of the flight envelope is a foundation for other subjects to carry out.

In flight flutter testing, level flight and dive flight of the aircraft is required to reach the V_{DF}/M_{DF} envelope. In flight test, different kinds of excitations (Control Surface Pulses, Oscillating Control Surfaces, Thrusters, Inertial Exciters, Aerodynamic Vanes, Dynamic Engineering Incorporated (DEI) rotating cylinder exciters, Random Atmospheric Turbulence) are used to excite the aircraft structure. The critical flutter mode response is recorded, and then damping and frequency characteristics are analyzed. The aeroelastic stability of the vehicle is examined by the trend of vibration accelerometer response data, damping and Power Spectral Density (PSD) [4-7].

Risk of the flight flutter test is so high that the real-time monitoring is necessary. The aeroelastic stability of the vehicle is continuously monitored during flight flutter test in a dedicated ground station facility. Accelerometers, strain gages, or both are mounted on the test vehicle to measure structural response[11]. These transducer outputs are telemetered by the ground station and displayed on strip charts. The traces are observed for sinusoidal motion and unusual modal activity throughout the test. For onboard excitation, such as frequency sweep, dwell, and control surface pulses, the rate of decay for the modes excited is also monitored.

Real-time frequency spectral analysis displays are used to monitor the change in modal energy for important modes during the flight, particularly when the vehicle is being accelerated to the next higher airspeed. Usually, the modes that are involved in a critical flutter mechanism, such as wing bending and torsion mode, that are monitored on these displays simultaneously to observe frequency coalescence trends.

Software is implemented to estimate frequency and damping of critical structural modes during the flight flutter test. The frequency and damping of structural modes are plotted as a function of airspeed clearance to the next higher airspeed point is given by the flutter test director referencing analysis results. The Pilot Comments and Structural Inspection of control and vibration are also important for flight safety.

However, time domain accelerometer on strip charts monitoring is the most mainly, critical, exact parameter and method, which has a high credibility in flight flutter test safety control. The frequency, damping and Power Spectral Density (PSD) are secondary parameters after time domain signal identification. In-flight Emergency Egress Plan should be set to ensure safety of flight flutter test. The vibration level is detailed so that the acceleration monitoring is convenient for ground engineer. The maximal acceleration of wing tip, horizontal tail tip, fin tip in every test point is set to monitoring the strip charts. This different vibration response level in different test point monitoring didn’t consider in the maximal acceleration monitoring method. Such monitoring method has low accuracy for the testing process. Once the trace instability of airplane appears, the flight flutter stability boundary is difficult to be predicted, and the safety and project of flight flutter test will be influenced.

Before flight flutter test, the benefit of aeroelastic response simulation of different excitation method in flight flutter test as follows.

(1) The airplane structure acceleration, displacement detail parameters in test point could be obtained with monitoring reference;

(2) The stability of airplane will be estimated by time domain dynamic parameters;

(3) The relation between input excitation amplitude and output response amplitude can be estimated as a reference in flight flutter test excitation setting.

To improve the flight flutter test safety and schedule, the flight flutter testing and response simulation for different kinds of excitation techniques is needed to study. The structure vibration response and stability characteristics in flight flutter test point can be obtained by aeroelastic response simulation technique under different kinds of excitations. Quantities of parameters needed in real-time stability monitoring are also obtained, and the excitation force level and response amplitude in real-time test can also be estimated.

3 Aeroelastic response simulation framework for flight flutter test

The Aeroelastic Response Simulation framework with different Kinds Of excitations In flight flutter testing is shown in Fig.1. Detailed items are as follows:

(1) Define Test Point;

(2) Build dynamic finite element model for flight flutter test airplane configuration;

(3) Based on test point parameters, to build the different flight test excitation model for aileron, rudder, elevator, wing tip, fin tip, horizontal tail tip, and so on in sweep excitation, pulse excitation, dwell excitation and turbulence excitation;

(4) Conduct the analysis to the different flight test excitation model for aileron, rudder, elevator, wing tip, fin tip, horizontal tail tip, and so on in sweep excitation, pulse excitation, dwell excitation and turbulence excitation;

(5) Deal with and analysis result and estimate the response results and stability results about acceleration, displacement, damping parameters, and all resulting parameters stored in data-base test;

(6) The detail parameters at every test point will be used in flight flutter testing. If the airplane is dynamically stable, the next test point will be conducted. Otherwise, the flight flutter test will stop in this point.

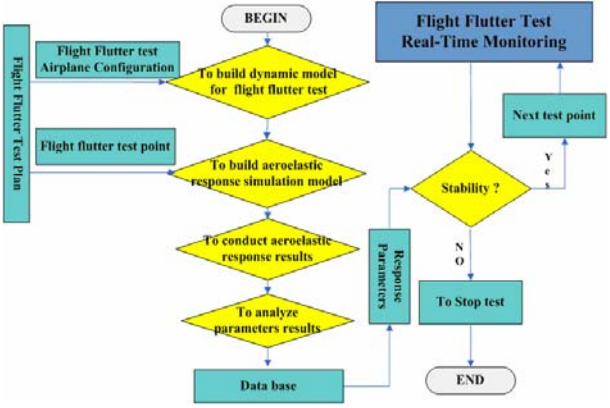


Fig.1 Aeroelastic response simulation framework with different kinds of excitations in flight flutter testing.

Usually, there would be 20 to 40 test points in flight flutter test. The response results of different airplane location should be obtained at different flutter excitation case in every test points. The parameters results come from the aeroelastic response simulation of flight flutter test. The analysis parameters will be compared with the flight test results in data base stored to estimate stability of airplane.

4 Aeroelastic response simulation method of flight flutter test

4.1 Modeling for aeroelastic response simulation of flight flutter test

The dynamic finite element model of full scale airplane structure has been developed in MSC.NASTRAN system. The beam structural scheme is also used in these models base on mass and stiffness. The model should be modified according to ground vibration test results, which normal mode characteristic should be the same with analysis and test results.

For the aeroelastic response dynamic finite element model, the fuel, fuselage cabin loads and balance weights of the configuration should match with flight flutter test airplane configuration. The rotation frequency of control surface such as aileron, elevator and rudder should also match with the control surface vibration frequency test results before flight flutter test.

4.2 Excitation modeling for aeroelastic response simulation of flight flutter test

The different excitation model of aeroelastic response should be built at different test points which include altitude, air density, Mach number, velocity, weights, CG parameters. The typical model include symmetric and antisymemetric on aileron(sweep and impulse),elevator(sweep and impulse), rudder(sweep and impulse),wing tip(sweep), horizontal tail(sweep), fin(sweep).

(1) Control surface sweep excitation model

The rotation angle of control surface is the input of sweep and impulse in excitation signal. The sweep sine function is as follows:

$$A(f) = A_0 \sin(2\pi f + \varphi) \qquad (1)$$

where f is frequency, φ is original phase, A_0 is amplitude, A is excitation amplitude.

The frequency of linear sweep in time domain is as follows:

$$f(t) = \frac{(f_{end} - f_{start}) \times t}{T} + f_{start}, \qquad (2)$$
$$0 < t < T$$

where f is transient frequency, f_{start} is start frequency, f_{end} is end frequency, T is excitation time, t is transient time.

(2) Control surface impulse excitation model

The rotation angle of control surface is the input of impulse in excitation signal. The impulse function is as follows:

$$A(t) = \begin{cases} A, t - 0.5T \le t \le t + 0.5T \\ 0, t = else \end{cases} \qquad (3)$$

where A is amplitude, T is impulse excitation time, t is time.

(3) Inertial exciters excitation model

The inertial exciters excitation model that conducts sweep excitation is the same with control surface sweep excitation equation (1), but the input amplitude is force.

(4) Random atmospheric turbulence

Atmospheric turbulence is mainly random process. The vertical gust excitation model[8] is as follows:

$$F(t) = WG \bullet PSD(t) \bullet (t - \frac{x - x_o}{V}) \qquad (4)$$

where $F(t)$ is force, $WG = \frac{V_{gust}}{V_{vehicle}}$ is gust factors, $PSD(t)$ is gust PSD function, t is time, V is velocity, x is air stream location, x_o is the gust reference point location.

4.3 Aeroelastic response analysis with respect to flight flutter excitation

Airplane aeroelastic response analysis in conducted in MSC.NASTRAN[8] SOL146 model. The aeroelastic response analysis in modal coordinates has a basic equation (5) of the form.

$$\left[-M_{hh}\omega^2 + iB_{hh}\omega + (1+ig)K_{hh} - \frac{1}{2}\rho V^2 Q_{hh}(Ma,k)\right]\{u_h\} = \{P(\omega)\} \qquad (5)$$

where M_{hh} is modal mass matrix, B_{hh} is modal damping matrix, K_{hh} is modal stiffness matrix, Q_{hh} is modal aerodynamic force matrix, which is a function of parameters such as Mach number Ma and reduced frequency $k = \frac{\omega \bar{c}}{2V}$, $\omega = 2\pi f$ is circular frequency, f is cycle frequency, $\bar{c}$ is reference chord length, V is velocity, ρ is air density, $p = \omega(\gamma \pm i)$ is eigenvalue, $g = 2\gamma$ is artificial structural damping, γ is transient decay rate coefficient, u_h is modal amplitude vector, $P(\omega)$ is total generalized loads, including the generalized load due to the aerodynamic gust $PHF_2(\omega)$ and non-aerodynamic generalized loads $PHF(\omega)$.

$$\{P(\omega)\} = \{PHF_2(\omega)\} + \{PHF(\omega)\} \qquad (6)$$

The airplane mass, stiffness and aerodynamic is considered in aeroelastic response analysis.

The acceleration and the displacement of time domain or frequency domain in flight flutter test point is obtained for wing tip, horizontal tail tip, and fin tip location. All the results are stored in data-base which can serve as reference in flight flutter test strip charts monitoring.

4.4 Stability determination

According dynamic stability theory, the aeroelastic system could be classified as stable system, critically stable system or unstable system. Stable system always leads to stable response whereby the amplitude of the time history remains convergent. Critically stable system leads to a critical stable response whereby the amplitude of the time history remains constant. Unstable system leads to an unstable response whereby the amplitude of the time history is divergent. The damping level for the airframe should be considered in all analysis.

5 Examples of aeroelastic response example for flight flutter test

Aeroelastic response under flight flutter test excitations is studied to demonstrate that the response simulation technique with the excitation model of flight flutter test is valid and feasible in engineering applications. Aeroelastic response simulations of four numerical test cases are conducted. The first application is the 15-deg sweptback wing under an impulsively applied load at the wing tip in order to investigate the transient response at subcritical, critical, and supercritical speeds, and the flutter stability examination is presented. The second application uses aileron excitation response simulation to examine the flutter stability of a transport airplane. The third application uses a transport airplane aileron excitation response simulation results in comparison with flight flutter test results, the result agrees well with each other. The fourth application uses a transport airplane model that conducts the Oscillating aileron sweep excitation, Aileron Pulses excitation, wing tip Inertial Exciters excitation and Random Atmospheric Turbulence excitation techniques in aeroelastic response simulation and the results are analyzed.

5.1 Aeroelastic response of a 15-degree sweptback wing with an impulse force applied at tip (Example 1)

The simple flat-plate wing with 15-degree sweptback is a classical flutter model. This wing has been tested in a wind tunnel for flutter at subsonic and supersonic speeds and the results have been reported early by Tuovila and McCarty(1955) and investigated further by Yates and Bennett(1963). The 15-degree sweepback wing was analyzed by Rodden, Harder and Bellinger (1979) with its structure idealized as a “stick” model and with aerodynamic forces calculated by the Doublet-Lattice subsonic lifting surface theory (DLM)[9]. The 15-deg of sweptback wing Structure model is shown in Fig.2. The wing flutter speed is 147.2m/s, and the aeroelastic response displacement is investigated with an impulsive load now applied at the wing tip. The loading is applied at GRID 40 at the tip trailing edge of the wing in the vertical direction. The response is output at GRID 24 at wing tip mid chord. The two impulse excitation is input in 0.4s excitation time. The frequency is 5Hz with a period of 0.2s. The aeroelastic response amplitude behavior is small and stable as expected at 127m/s which is well below the flutter speed 147.2m/s. The response amplitude becomes much larger and larger as speed increasing. The airplane response is stable at 146.0m/s(Fig. 3a). The airplane response amplitude is constant at the critical flutter speed 147.2m/s(Fig. 3b). The airplane response amplitude is unstable at 148.6m/s over flutter speed(Fig. 3c).

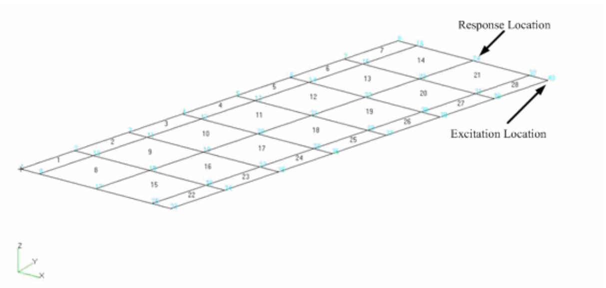
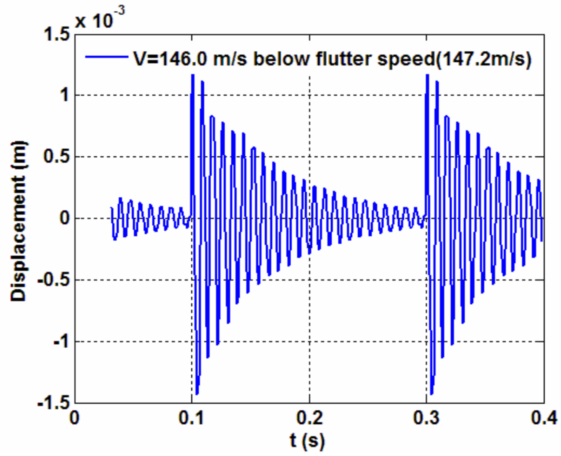
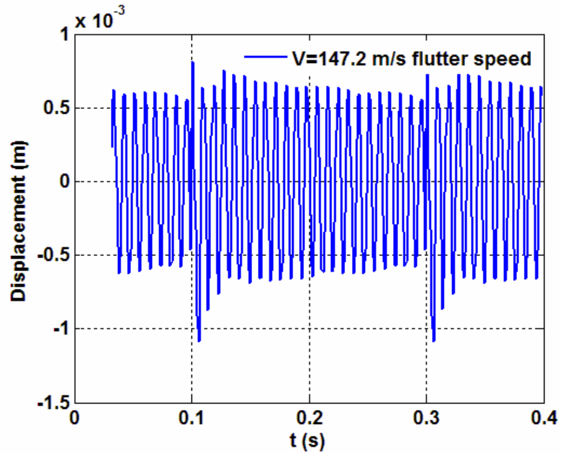


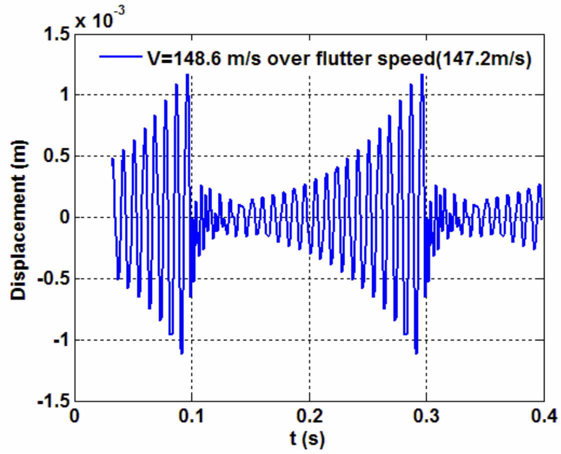
Fig. 2 A 15-degree sweptback wing finite element model.



a) V=146.0 m/s, Stable



b) V=147.2m/s, Critical Stable

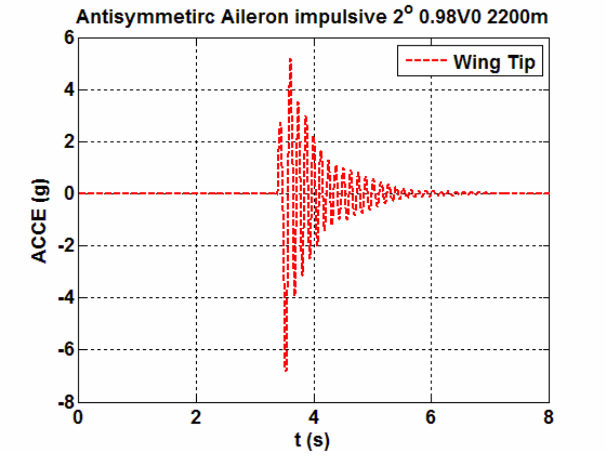


c) V=148.6m/s, Unstable

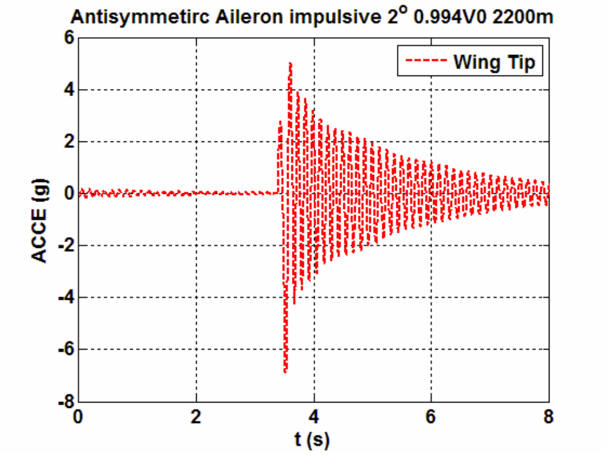
Fig. 3 Time-history of wing tip response with the wing tip pulse excitation at flutter stability boundary.

5.2 Airplane aileron impulse excitation simulation(Example 2)

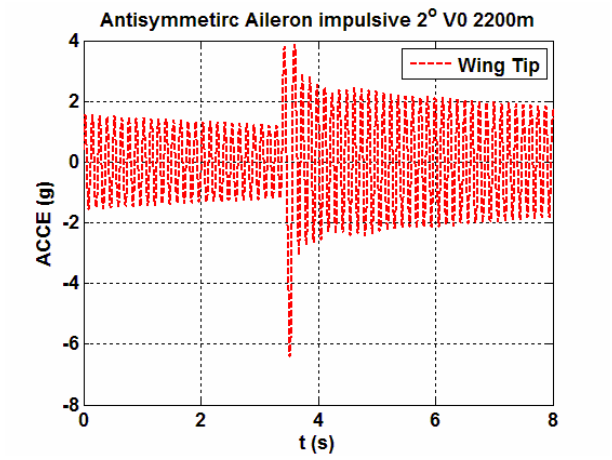
A airplane aileron antisymmetric impulse excitation is simulated nearby flutter speed V0 at altitude 2,200m. The rotation angle of aileron is 2 degree, the aeroelastic response displacement is investigated at the wing tip. The aeroelastic response amplitude behavior is small and stable as expected at 0.98V0 and 0.994V0 below the flutter speed. The response amplitude becomes much larger as speed increase. The airplane response is stable at 0.98V0 and 0.994V0 (Fig.4a and Fig.4b). The airplane response amplitude is constant at critical flutter speed V0 (Fig.4c). The airplane response amplitude gets unstable at 1.003V0 over flutter speed (Fig.4d).



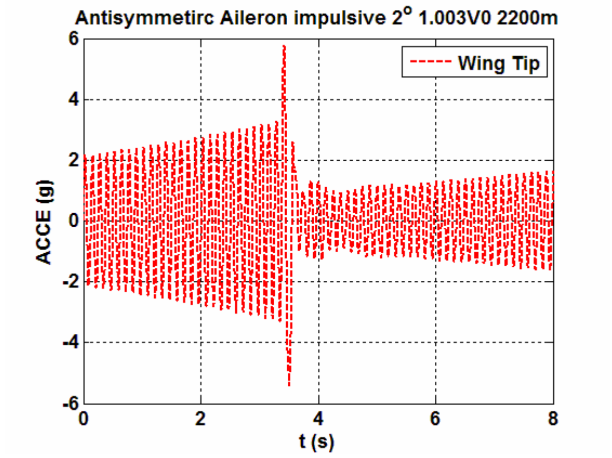
a) V=0.98V0, Stable



b) V=0.994V0, Stable



c) V=V0, Critical Stable

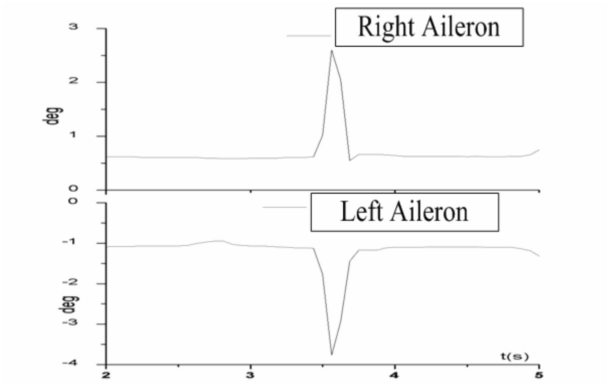


d) V= 1.003V0, Unstable

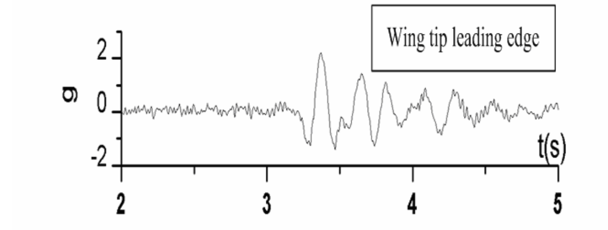
Fig. 4 Time-history of wing tip response with the aileron impulse excitation at flutter stability boundary.

5.3 Airplane aileron impulse excitation results and test validation.(Example 3)

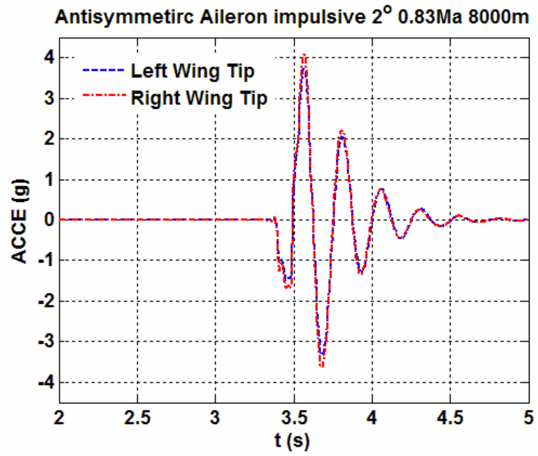
An airplane aileron antisymmetric impulse excitation results is validated with flight flutter test at altitude 8,000m, 0.83 Mach, the rotation angle of aileron is 2 degree. The aeroelastic response acceleration is investigated at the wing tip. Time history of the angle of aileron for aileron impulse excitation is shown in Fig.5 (a). The flight flutter test results is shown in Fig.5 (b), and the analysis results is show in Fig5. (c). The results agree well especially for the first peak acceleration response is about 1.5g and the response is well damped after 5 peaks as shown in time-history. The airplane is stable, thus no flutter occurs.



a) Time history of the angle of Aileron in aileron impulse excitation



b) Flight flutter test results



c) Aeroelastic response analysis results

Fig. 5 Time-history of left wing tip response with antisymmetric aileron impulse excitation at 0.83Mach and altitude 8,000m.

5.4 Aeroelastic response prediction of flight flutter test in aileron sweep, aileron impulsive, wing tip inertial sweep and turbulence excitation(Example 4).

For a civil airplane, the aeroelastic acceleration response had been obtained with aileron sweep, aileron impulse, wing tip inertial sweep and turbulence excitation. And the flutter stability is investigated in this example. At Flight flutter test point, design dive Mach number M_D is 0.89, altitude is 8000m, velocity is 274m/s, dynamic pressure is 19768Pa.

Table 1. Excitation signal list for flight flutter test.

No.	Excitation Location	Analysis Type	Excitation Signal Type	Excitation Amplitude (Degree or N)	Excitation Frequency (Hz)
1	Aileron	Frequency Domain Analysis	Sweep Sine Linear	0.3°	1~30
2	Aileron	Time Domain Analysis	Dwell Sine Linear	0.3°	4.1, 5.6, 10.5
3	Aileron	Time Domain Analysis	Pulse Triangle	3.0	——
4	Wing tip	Frequency Domain Analysis	Inertial Sweep Sine Linear	1000N	1~30
5	Wing tip	Time Domain Analysis	Inertial Dwell Sine Linear	1000N	10
6	Full Airplane	Frequency Domain Analysis	Turbulence Random	Wg=3.65e-6	0~10
7	Full Airplane	Time Domain Analysis	Turbulence Random	Wg=3.65e-6	5

Details of the excitation signal of aileron sweep, aileron impulse, wing tip inertial sweep and turbulence is shown in Table 1. Time history for the excitation Force are shown in figs.6~8 for the 4.1Hz, 5.6Hz,10.5Hz aileron dwell sweep excitation, respectively. Angle of Aileron for the aileron impulse excitation is shown in fig.9.

Frequency-spectrum of wing tip response with the aileron sweep excitation at M_D and altitude 8,000m is show in fig.10. Time-history of wing tip response for the mode peak frequency 4.1Hz,5.6Hz,10.5Hz aileron dwell sweep excitation at M_D and altitude 8,000m is show in Figs.11~13, respectively. The aeroelatic response results show good agreement between frequency domain and time domain simulation techniques for aileron sweep excitation.

Time-history of wing tip response to the aileron impulse excitation at M_D and altitude 8,000m is shown in fig.14. Airplane wing tip acceleration amplitude becomes much smaller as time increasing, the airplane is stable and no flutter occurs, a good flutter margin is adequacy.

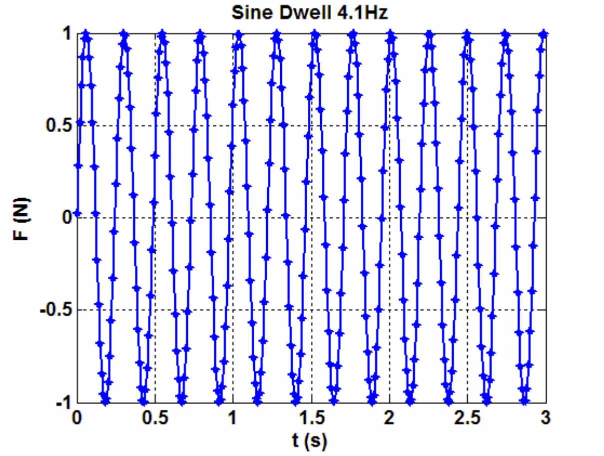


Fig. 6 Time-history for the excitation force with 4.1Hz aileron dwell sweep excitation.

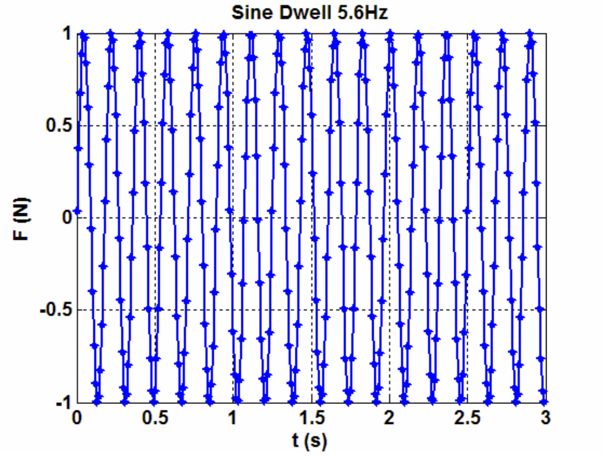


Fig. 7 Time-history for the excitation force with 5.6Hz aileron dwell sweep excitation.

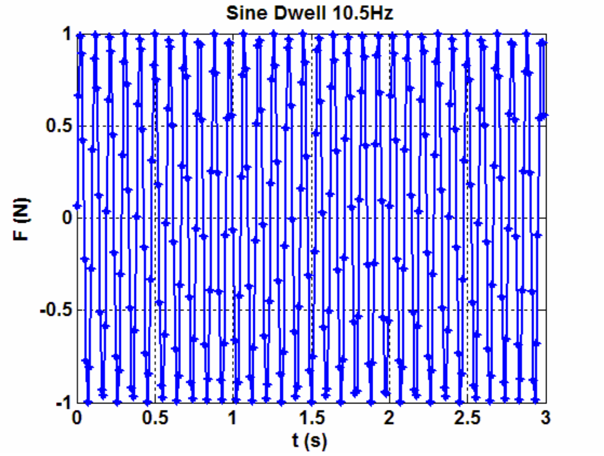


Fig. 8 Time-history for the excitation force with 10.5Hz aileron dwell sweep excitation.

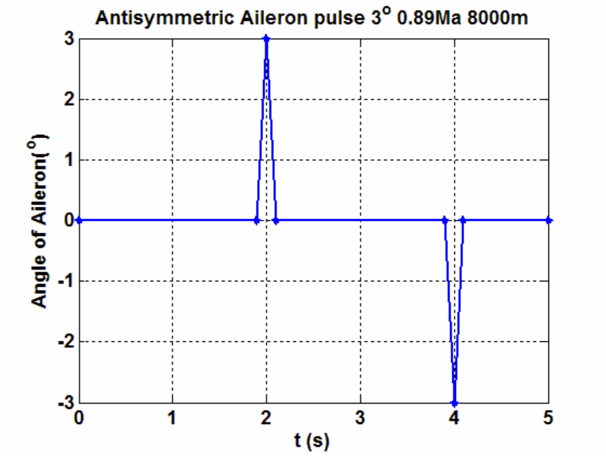


Fig. 9 Angle of aileron for aileron impulse excitation.

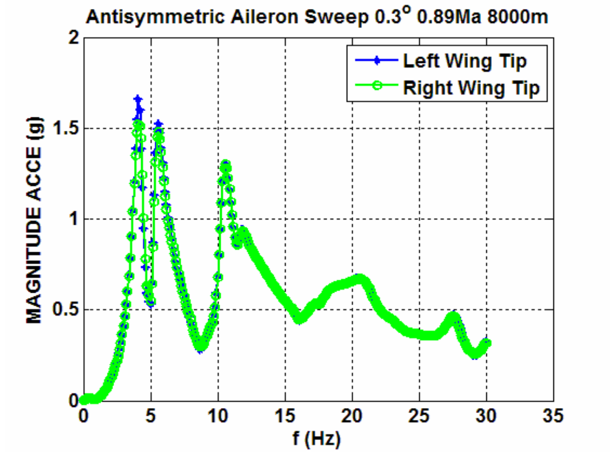


Fig.10 Frequency-spectrum of wing tip response to the aileron sweep excitation at M_D and altitude 8,000m .

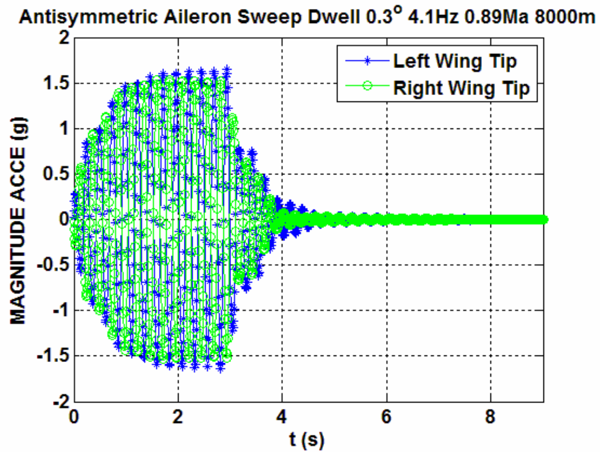


Fig. 11 Time-history of wing tip response to the 4.1Hz aileron dwell sweep excitation at M_D and altitude 8,000m.

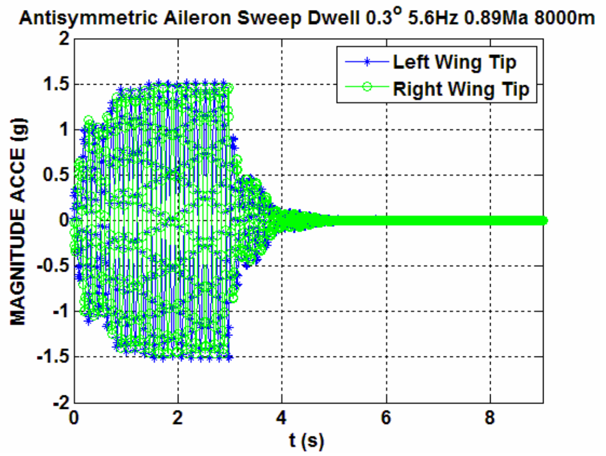


Fig. 12 Time-history of wing tip response to the 5.6Hz aileron dwell sweep excitation at M_D and altitude 8,000m.

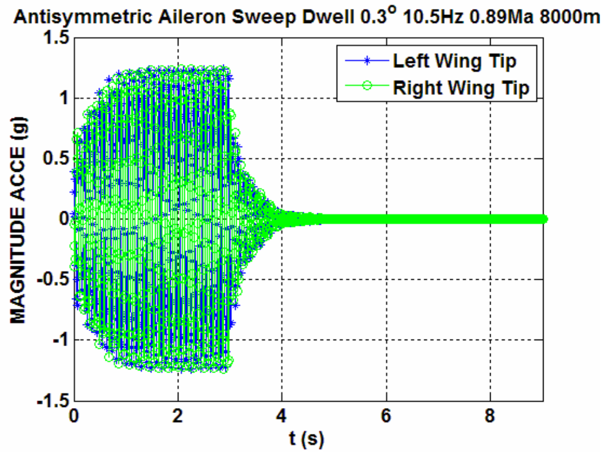


Fig. 13 Time-history of wing tip response to the 10.5Hz aileron dwell sweep excitation at M_D and altitude 8,000m.

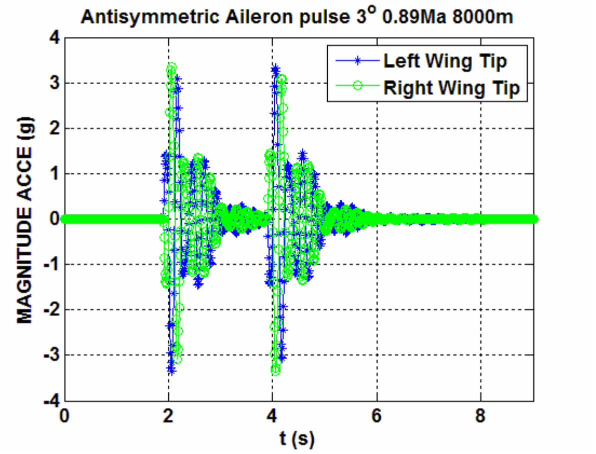


Fig. 14 Time-history of wing tip response to the aileron pulse excitation at M_D and altitude 8,000m.

Frequency-spectrum of wing tip response to the wing tip inertial exciters sweep excitation at M_D and altitude 8,000m is show in Fig.15. Time-history of wing tip response to the peak mode frequency 4.1Hz, 5.6Hz, 10.5Hz dwell wing tip inertial exciters excitation at M_D and altitude 8,000m is shown in Figs.16~18, respectively. Airplane wing tip acceleration amplitude becomes smaller and smaller as time increasing, and the airplane is stable thus no flutter occurs.

Frequency-spectrum of wing tip response to the turbulence excitation at M_D and altitude 8,000m is shown in Fig.19. Time-history of wing tip response to the impulse 5Hz and turbulence excitation at M_D and altitude 8,000m is shown in Fig.20. Airplane wing tip acceleration amplitude gets smaller and smaller as time increasing, and the airplane is stable thus no flutter occurs.

The results of control surface, inertial and turbulence excitation show that both low frequency modes and high frequency modes can be excited by control surface pulse, while inertial excitation can only excite low frequency modes. The response amplitude is quite small under turbulence excitation, and only low frequency modes can be excited.

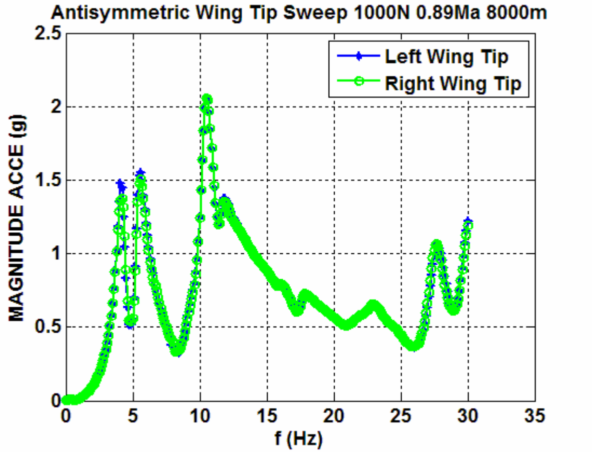


Fig. 15 Frequency-spectrum of wing tip response to the wing tip inertial exciters sweep excitation at M_D and altitude 8,000m.

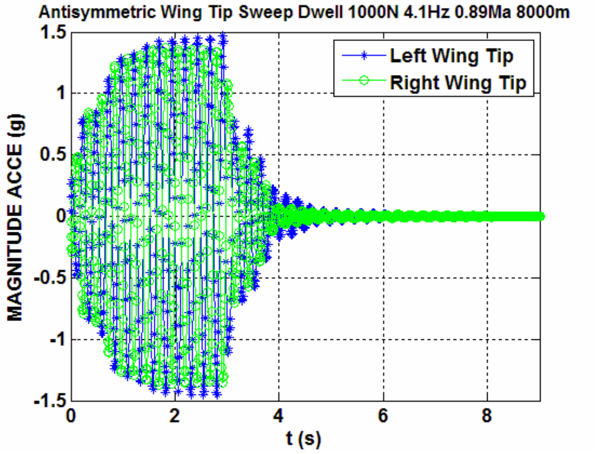


Fig. 16 Time-history of wing tip response to the 4.1Hz dwell wing tip inertial exciters excitation at M_D and altitude 8,000m.

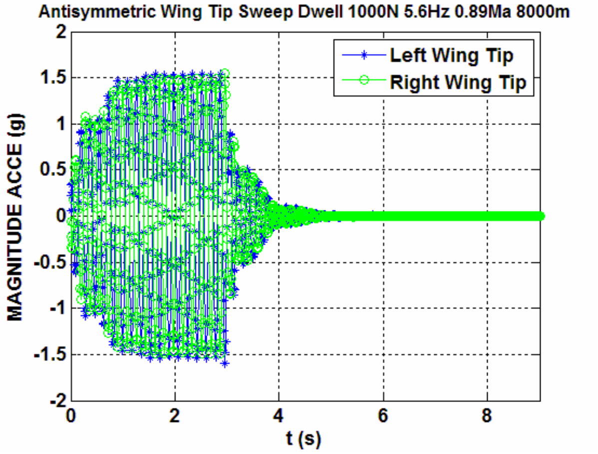


Fig. 17 Time-history of wing tip response to the 5.6Hz dwell wing tip inertial exciters excitation at M_D and altitude 8,000m.

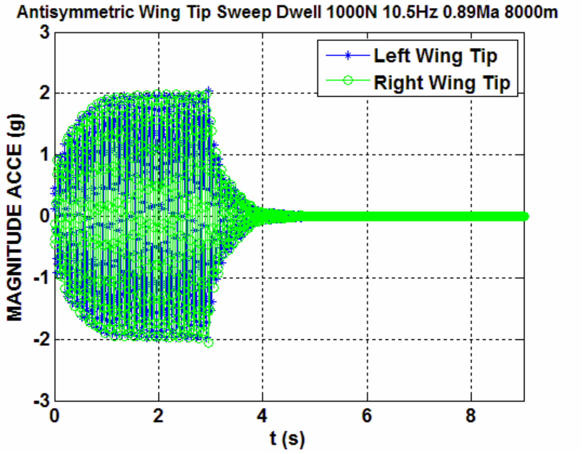


Fig. 18 Time-history of wing tip response to the 10.5Hz dwell wing tip inertial exciters excitation at M_D and altitude 8,000m.

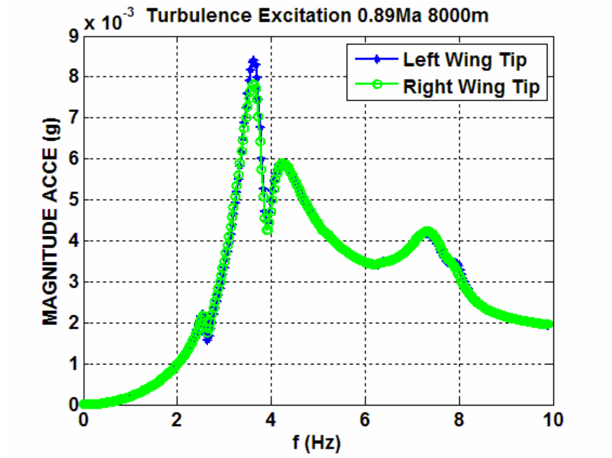


Fig. 19 Frequency-spectrum of wing tip response to the turbulence excitation at M_D and altitude 8,000m.

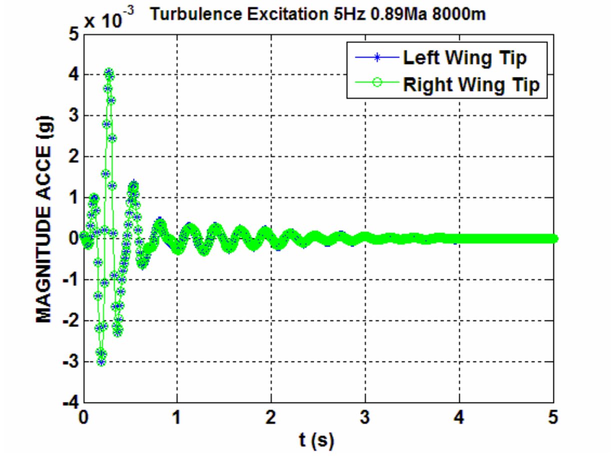


Fig. 20 Time-history of wing tip response to the 5Hz turbulence excitation at M_D and altitude 8,000m.

These four flight flutter test example application demonstrate that the aeroelastic response simulation technique under the excitation of flight flutter test is valid and feasible in engineering. The flutter stability could be predicted and aeroelastic response of different modes could be acquired by this method.

6 Future Research and Development

Flight flutter testing and aeroelastic response simulation technique under different kinds of excitations still needs to be developed and implemented. Techniques such as follows should be considered in future research and development:

(1) The effects of high Mach number (Near Mach 1.0) unsteady aerodynamic force on aeroelastic response simulation results;

(2) The effects of damping level for different aircraft on aeroelastic response simulation results;

(3) The aero-server-elastic response with control law items.

7 Conclusions

The characteristics of flight flutter test and stability monitoring are presented in this paper. The flight flutter test and aeroelastic response simulation for different excitation techniques is brought forward. These four flight flutter test example applications demonstrate that the response simulation technique under the excitation of flight flutter test is valid and feasible in engineering. Finally, comments regarding the direction of future research are presented in response simulation technique with flight flutter test excitation.

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