Overview of Recent Flutter Test Key Techniques for Modern Civil Aircraft Inspection Airworthiness

Xie Jiang\(^1\), Yang Fei\(^2\) and Liang Ji\(^2\)

\(^1\) Tianjin Key Laboratory of Civil Aircraft Airworthiness and Maintenance, Civil Aviation University of China, Tianjin 300300, China
\(^2\) Shanghai Aircraft Design and Research Institute of COMAC, Shanghai 200232, China

Corresponding author: Yang Fei (yangfei@comac.cc)

Abstract: The aim of flight flutter test is to determine the aeroelastic stability for new and modified research vehicles in the desired flight envelope. Many new requirements and challenge are presented for flight flutter test in modern high-performance civil aircraft design and project. In response to the concerns of the aeroelastic community, researches are conducted to improve the flight flutter (including aeroservoelasticity) test process. The paper provides an airworthiness inspection experience for civil aircraft flight flutter test, which includes the airworthiness inspection foundation and airworthiness inspection content. And this paper also offers a brief practical guide to all key techniques involved in flight flutter stability verification of aircraft. The important elements of this summary so far include the following: (1) flight flutter test preparation; (2) flight flutter test techniques; (3) flight flutter test monitoring; (4) the aeroelastic response simulation framework with different kinds of excitations in flight flutter testing; (5) flutter prediction for flight flutter test; (6) flight flutter test risk control; (7) flight flutter test schedule and cost; (8) flight flutter test project management. This paper addresses these items using flight flutter test experience.

Keywords: Flutter, simulation, flight test, aircraft, airworthiness.

1. Introduction

Modern high-performance civil aircraft use thin, low-drag supercritical airfoils designed for maximum aerodynamic characteristic. Modern civil airplane 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 0.98 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) instabilities [2, 3]. Once the airplane flutter occurs in flight, the airplane would change from a stable safe state to another unstable unsafe state in approximately three seconds, the dynamic loads and stress would damage structure, resulting in flight accident [4].

The designed flight envelope for new and modified research aircraft is usually verified to be free of these instabilities through flight flutter testing, which is a challenge research region for cost, time and safety. During flight flutter test, the boundary of flutter stability is identified with accurate and effective method, the envelop expansion is done carefully and step wisely. The purpose of flight flutter test is to guarantee flight safety and program goes on wheels, the process and result is satisfied the airworthiness requirements. The flight flutter test is a flight item for group, department, and company in airworthiness inspection. To safely conduct flutter testing, proper test preparation, flutter monitoring methods, data reduction and airworthiness inspection are required. In addition, an accurate and reliable parameter
identification algorithm to estimate frequency and damping of critical structural modes is required to monitor the aeroelastic stability of the aircraft in flight flutter test [5-8]. The typical flutter boundary and damping requirement is showed in Fig. 1 [9]. In the past 40 years, the flight flutter test techniques have been researched, and flight flutter test were carried out for a lot of large and small aircraft or civil airplanes. The modern civil airplanes are designed according to airworthiness (Section 2). Because flight flutter test is the only MOC6 Flight test items in before TIA (type inspection authorizations), flutter testing is critical to any aircraft development, safety, process and cost program. This paper summarized the technology and management for flight flutter test, and discussed the airworthiness inspection experience (Section 3). The important elements of this summary so far include the following: (1) flight flutter test preparation; (2) flight flutter test techniques (Section 4); (3) flight flutter test monitoring; (4) the aeroelastic response simulation framework with different kinds of excitations in flight flutter testing; (5) flutter prediction for flight flutter test; (6) flight flutter test risk master; (7) flight flutter test schedule and cost; (8) flight flutter test project management.

2. The Airworthiness Requirements for Flight Flutter Test

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. Flight flutter testing expands the flight envelope from VMO/MMO to VDF/MDF or VD/MD. Opening of the flight envelope is a foundation for other subjects to carry out. Boundary requirements and damping requirements of the flight flutter testing is shown in Fig. 1. In flight flutter testing, level flight and dive flight of the aircraft is required to reach the VDF/MDF envelope. Flight flutter testing is a key subject to test the overall safety performance of aircraft. Flight flutter testing of civil aircraft is the only verification subject before obtaining the TIA and the first verification subject in airworthiness review. Therefore, whether the flight flutter testing of civil aircraft gets through the airworthiness review or not will influence not only the node of entering TIA directly but also the time node of obtaining airworthiness TC permit and delivering aircraft to airline.

3. Airworthiness Inspection Experience of Flight Flutter Test for Civil Airplane

The validation of large transport aircraft is a long process with complex techniques. Flight testing is the
final stage in airworthiness certification. The high risk in flight flutter test increases the complexity and difficulty. Airworthiness review increases the difficulty of civil aircraft flight flutter test, experience of civil aircraft flight flutter test is helpful for improving the level of flight flutter test.

3.1 The Airworthiness Inspection Foundation

The biggest difference between civil aircraft flight flutter test and military aircraft flight flutter test is airworthiness work. The basis of transport civil aircraft airworthiness certification is FAR25 [10], CCAR25 [11], civil aircraft flight flutter test is referring AC25.629-B (e), CCAR25.629 (e) to design and carried out. A lot of flutter calculation is required to acquire the law of influence to parts flutter characteristics and whole vehicle flutter characteristics from structural mass, inertia, surface stiffness, connection stiffness, PCU actuator stiffness, PCU actuator position, fuel weight distribution, payload and cargo, flight altitude, flight speed and mach number. Low-speed flutter model wind tunnel test, high-speed flutter model wind tunnel test and whole vehicle ground resonance vibration test is required if necessary to obtain the natural vibration characteristics. The exact flutter characteristic (critical flutter speed, critical flutter frequency, flutter mode damping, flutter coupled mode and flutter mechanism) is the key foundation for flight flutter test airworthiness inspection.

3.2 The Airworthiness Inspection Content

Flutter of aeroelastic involves the unfavorable interaction of aerodynamic, elastic, and inertia forces on structures to produce an unstable oscillation that often results in structural failure. The free from flutter aircraft design all-around includes the aerodynamic, structure, weight and weight distributing, stress, flight control. The ground vibration test GVT is a key node for the first flight, the flight flutter test FFT is a key node for the Type inspection Authorizations TIA Airworthiness inspection. Flight flutter testing provides the final verification of the analytical predictions throughout the flight envelope. In civil airplane design proceeding, the airworthiness inspection plan is supplement each other with design plan. In different phase of flight flutter test, the inspection items are established by Civil Aviation Authority according to the flight flutter test characteristic. The propose conducts flight flutter test work according to the airworthiness inspection plan and aircraft design plan. The responsibility of airworthiness inspection is to finish the inspection job in safe flight test. The details of airworthiness inspection for flight flutter test are based on flight flutter test plan and flight flutter test configuration evaluation report. Flight flutter test plan is one and only one as to be followed in flight flutter test, which is a detailed outline document. The flight flutter test plan includes flight foundation, flight test content, flight test methods and procedures, data reduction method and acceptable criteria. The flight flutter test configuration evaluation report is applicable to airworthiness compliance evaluation of aircraft configuration for flight flutter test. The hardware and software is evaluated. The hardware is FRR, material deviation forms, weight deviation due to knocked-down parts, configuration deviation due to unfinished item, configuration deviations resulted from series design modification. The software is configuration deviation due to autopilot and flight control system software. The flight flutter test configuration evaluation report is consistent with the flight flutter test plan. The weight in aircraft should be finished before flight flutter test to show the weight state. The measure of ensuring configuration is structure inspection, weight test, control surface frequency test, ground vibration test, software and design modification inspection evaluation. The modification item include trailing cone installation, vibration accelerometers, strain gauges, and flight parameter transducers, excitation system equipment,
The highlight technique requirements and design schedule determined many of the key techniques and important items for flight flutter test.

4.1 The Flight Flutter Test Preparation

The safe flight flutter test is needed to exact flutter prediction, which foundation is flight flutter test preparation. The aircraft mode and flutter characteristic is obtained through parameters analysis, flutter model wind tunnel test, ground vibration test GVT and so on. The flutter boundary for flight envelope, flutter critical mode frequency and damping, critical Mach number, critical fuel and payload must be cleared. The aero-servo-elastic ASE analysis should be conducted for pitch, yaw and roll control law.

4.2 The Flight Flutter Test Configuration Management

The aircraft configuration of flight flutter test is the TC design configuration. The weight test must be conducted to affirm the weight state before flight flutter test. The ASE flight test needs to clear the state of avionics and flight control system. The flight test modified equipment, the vibration accelerometers should be installed in the interested structure localization to track the mode, which is wing, horizontal stabilizer, fin vertical bending mode, side bending mode, torsion mode, engine pitch mode, yaw mode and roll mode, winglet bending mode and torsion mode, flap bending mode and rotation mode, slot bending mode and rotation mode, aileron, elevator and rudder rotation mode. The fuel or payload weight should be set in everyone test point according to flight flutter test plan.

Because the flow turbulences influence is strong during flight flutter test, the nose of high speed flight is so big that makes the mode parameter estimation difficulty. Flight flutter test requires sufficient excitation to excite the modes shown by analysis to be the most likely to couple for flutter. The method of excitation must be appropriate for the mode response frequency and damping being investigated. The accurately mode data can not be selected if the excitation is too weakly. On the other hand, the aircraft structure could be damaged if the excitation is too strong. Excitation methods may include control surface motions or flight pilot pulse or internal moving mass or external aerodynamic exciters or flight turbulence [12, 13], and the different excitation method is shown in Table 1 [14]. The symmetry and anti-symmetry sine sweep or dwell excitation during sweep. The anti-symmetry mode could be got by aileron excitation, while the symmetry mode could be got by elevator excitation, and the asymmetry mode could be got by rudder excitation. The useful linear sweep frequency range is 0-10 Hz, and the useful logarithm sweep frequency range is 10-40 Hz. The critical flutter mode is useful in sweep dwell excitation, and the excitation time is 3 to 5 s. For the large transport aircraft, the low 5 Hz mode could be excited through flight pilot pulse excitation. Because

<table>
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<th>Method Items</th>
<th>Pulse Items</th>
<th>Sweep Items</th>
<th>Random Items</th>
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<tr>
<td>Control surface pulse</td>
<td>Oscillating control surfaces</td>
<td>Aerodynamic vanes</td>
<td>DEI (dynamic engineering incorporated) rotating cylinder exciters</td>
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<tr>
<td>Thrusters</td>
<td>Inertial exciters</td>
<td>Random atmospheric turbulence</td>
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flutter mode frequency is low, the control surface could satisfy the flight flutter test requirements.

In flight flutter test, the flight test point for flight envelope expansion from MMO to MDF accomplished by a series of constant altitude diving or constant Mach diving. The flight rule is from highest altitude to lowest altitude, from lowest dynamic pressure to highest dynamic pressure. A flight flutter test programs should be planned according to flutter testing results and analysis results. The data obtained at each stabilized test point establish a damping trend as a function of airspeed. Information is then extrapolated to predict the stability of the next planned test point by damping prediction or Zimmerman and Weissenburger prediction to warn of the onset of flutter and margin flutter. Engineers relying on intuition and experience, are limited to real-time monitoring of sensor responses on strip charts to ensure flight safety.

4.4 The Flight Flutter Test Monitoring

The flight flutter test risk 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. These transducer outputs are telemetered to 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.

4.5 The Aeroelastic Response Simulation Framework with Different Kinds of Excitations in Flight Flutter Testing

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) 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 PSD (power spectral density) [5, 6, 9].

Risk of the flight flutter test is so high that the real-time monitoring is necessary. 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 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 did not 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.

The aeroelastic response simulation framework with different kinds of excitations in flight flutter testing is shown in Fig. 2. 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.

The simple flat-plate wing with 15-degree sweptback is a classical flutter model. This wing has

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**Fig. 2** Aeroelastic response simulation framework with different kinds of excitations in flight flutter testing.
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) [15]. The 15-deg of sweptback wing Structure model is shown in Fig. 3. The wing flutter speed is 147.2 m/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 0.2 s. The aeroelastic response amplitude behavior is small and stable as expected at 127 m/s which is well below the flutter speed 147.2 m/s. The response amplitude becomes much larger and larger as speed increasing. The airplane response is stable at 146.0m/s (Fig. 4a). The airplane response amplitude is constant at the critical flutter speed 147.2m/s (Fig. 4b). The airplane response amplitude is unstable at 148.6 m/s over flutter speed (Fig. 4c).

The flight flutter test example application demonstrates 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.

4.6 Flutter Prediction for Flight Flutter Test

Flight flutter test is a hazardous and expensive flight test, flutter prediction is a effective method to minimize the risk and reduce the cost of the flight flutter testing. The flutter prediction method currently include the Zimmerman-Weissenburger flutter margin [16], extrapolating damping trends [4], envelope function [17], discrete autoregressive moving average model [18], and the flutter meter [19]. These methods have been evaluated by the flight test community on simulated data and flight-test/wind-tunnel data to deliver the flutter prediction capability. Most of these methodologies require either an accurate damping and frequency estimation of aircraft. A frequency-domain system-identification method called polyMAX [20, 21], is introduced to extract the aeroelastic modes from the frequency response function or power spectrum of the output parameter constraint setting and combination of the stabilization diagram, the damping ratio and frequency of the aeroelastic modes can be extracted consistently and accurately.

A new method, based on singular value decomposition and QR factorization [8], has been developed and applied to the analysis of F-18 flutter flight test data. The method is capable of identifying

![Fig. 3 A 15-degree sweptback wing finite element model.](image_url)
the frequency and damping of the critical aircraft modes, those responsible for the flutter phenomenon. The procedure relies on the capability of singular value decomposition for the analysis, modeling, and prediction of data series with periodic features and also on its power to identify matrix rank. The analysis of simulated and real flutter flight test data demonstrates the effectiveness, robustness, noise-immunity, and the capability for automation of the method proposed under specific conditions.

4.7 The Flight Flutter Test Risk Master

The risk of flight flutter test is various, which could be increased by control surface overweight, hinge gap, calibrate airspeed and so on. The E-6, a derivative of the Boeing 707 airframe, during a flight flutter test on Feb. 16, 1989, a divergent dynamic response occurred and the upper one third of the vertical fin, part of the rudder, and part of the tab were lost. On Sept. 28, 1989, a second flutter incident occurred resulting in the upper one third of the vertical fin, half of the rudder, and all of the tabs lost.

(1) Control surface overweight

Because of the manufacture deviation forms for structure, it could be resulted in control surface overweight configuration that dissatisfies the design configuration. The effect of control surface overweight for flutter characteristic must be evaluated before flight flutter test. The control surface rotational frequency check test should be conducted prior to the flight flutter test, which could reduce the risk of flutter flight test.

(2) Hinge gap

The hinge gap of aileron, rudder and elevator could be accreted for manufacture deviations, attrite in service and so on. The control surface hinge moment and stress should be monitored and analyzed in flight flutter test, to prevent limit cycle oscillation LCO.

(3) Calibrated airspeed

Flight flutter test is the first airworthiness inspection item and expand flight envelope from \( V_{MO}/M_{MO} \) to \( V_{D}/M_{D} \). The flight flutter test is prior to high speed flight and calibrated airspeed flight test. Accurate flight parameters should be taken by equipment in aircraft to ensure flight safe. As the same
to civil aircraft flight flutter test, pressure altitude, Mach number and indicated airspeed should normally be taken from the nose boom/trailing cone (X-ADC), not the difference GPS method. The flight data validity, safe flight test, fast schedule and airworthiness inspection could be benefited.

4. In-flight emergency egress plan
In-flight emergency egress plan should be set to ensure safety of flight flutter test. The vibration level is detailed so that the accelerometer monitoring is convenience by ground engineer.

5. Flight flutter test report
The flight flutter report is the most important document for airworthiness inspection, the international rule is necessary in content, format, data form, description. The flight flutter test plan should be proved through flight flutter test report. The critical mode parameters should be included in every test point, and the aircraft instability and airworthiness coincident for flight flutter test should be given in result.

4.8 The Flight Flutter Test Schedule and Cost
The cost of flight flutter test is related to the flight sortie and schedule. The flight sortie is related to the test point number, the less test point, the less flight sortie, the less diving flight, the less cost. The less configuration case of flight flutter test, the less cost.

The main influence factor is altitude, configuration and content for flight flutter test schedule. Firstly, flight altitude should cover the flight design envelope, the cruise altitude and right boundary envelope subsection altitude should be included at least. The more flight test altitude, the more test point, the longer flight test schedule, the more cost. Secondly, configuration case of flight flutter test is empty weight, fuel weight and payload weight. If flutter model wind tunnel test showed that the fuel weight and payload weight have little influence on the full-scale flutter characteristics and flight flutter test results, the configuration of fuel and payload weight could not be considered. Otherwise, they should be included. The configuration of fuel and payload weight will increase the flight sortie, flight test schedule. Thirdly, flight flutter content, the airplane has a proper margin of damping at all speeds up to VDF/MDF, and that there is no large and rapid reduction in damping as VDF/MDF level flight or dive flight. The Wind-UP-Turn as a shock induced flutter phenomena has been encountered on testing of aircraft such as the B-1 with supercritical type airfoils is not conducted. If Wind-UP-Turn is conducted, the flight risk is increased and the period is longer and the cost is more.

4.9 The Flight Flutter Test Project Management
Flight flutter test is related to a lot of companies and engineers, the relational specialty is abroad and technical level is higher. The schedule is urgency, and the project is strict. If flight flutter test would be favoring and speediness conducting, the flight flutter test project management must be scientific and reasonable, and every engineer’s positively should be inspired. The integration project team IPT of flight flutter test could be set to push flight test. The flight flutter test IPT group should include aircraft vice chief designer at least, flight flutter test manager, flutter group engineers (data reduction) and flight test engineers. The right of flight flutter test should be given to deal with every matter, avoiding to delay occasion resolve matter.

5. Conclusions
This paper summarized the flight flutter test techniques, conclusions are as following:

1. A perfect design is the foundation of flight flutter test project;
2. A staidness and particularity flight flutter test preparation ensure flight flutter test goes on wheels;
3. The fast and availability communication is a key loop for airworthiness inspection;
4. In-flight Emergency Egress Plan ensures the
safety of flight flutter test.

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