Flutter flight tests: a challenging benchmark for real-time methods

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Abstract. The framework of this paper concerns a phenomenon called "*flutter*" that is important in aeronautical applications. This phenomenon is a diverging vibration that results from a coupling between the structural dynamics of an airframe and the aerodynamic forces that act on it. This type of instability is quite critical since it can lead to the destruction of the aircraft within a couple of seconds. For this reason, every new aircraft is intensively flight-tested in order to demonstrate that flutter will not occur in all operating conditions.

This paper is an introduction to this session which gathers several articles on processing and identification techniques developed to detect any flutter tendency from flight test data. The objective of the paper is to describe the operational context of these tests which is very specific due to the hazardous nature of flutter. The constraints imposed by this testing environment on the processing methods are also specified.

Keywords. Detection, Flutter, Identification, Modal Analysis

1 Introduction

Among the various phenomenons that can affect the flight of an aircraft, flutter is one of the most feared one since this dynamic instability can lead to a sudden destruction of the airplane. One of the major goal of the flight testing campaign of any new aircraft is to check that, in any possible flight conditions, the airplane will be free of any flutter tendency.

This paper presents the general context of flutter testing and its consequences on the algorithms used to process flight test data to detect possible propensity for flutter. Because of the dangerousness of the flutter phenomenon and also of its possible sudden advent, these methods should comply with stringent requirements that are the subject of this paper.

This article is organized into two parts. The first one is devoted to the current or near-term context of flutter flight tests. Firstly we briefly describe the flutter phenomenon. We then outline the requirements to be met for the aircraft certification. The third point is devoted to the flutter surveillance procedure and the following one to the ensuing requirements for processing algorithms. Finally the last point is a brief account of the algorithms currently used at Airbus.

The second part deals with the future evolution of flutter testing. It is based on a study that was carried out in the FliTE2 Eurêka project. As reducing costs is nowadays a major issue, new testing procedures have to be devised in order to curtail the duration of flight tests while at the same time preserving the level of safety. The first point of this part describes a new and potentially more efficient way of carrying out flutter tests. Then two types of processing approaches are considered for this new testing procedure: a real-time tracking of the modes of the aircraft, the direct detection of the flutter tendency.

One goal of this paper is also to provide the academic community with a challenging application framework for new sequential algorithms. Several solutions that were developed during the FliTE2 project are presented in this session.

2 Current flutter testing approach

2.1 The flutter phenomenon

In the aeronautical domain, aeroelasticity is the science that studies the interaction among inertial, elastic, and aerodynamic forces of an aircraft. It was defined by Collar in 1947. Aeroelasticity deals with several phenomenons that may occur during the flight. Among these, flutter is the most hazardous one. It is a dynamic instability where the oscillations of the structure extract energy from the airstream. It can build up very quickly and cause the destruction of the aircraft.

Any physical object is subject to natural modes of vibration. When placed in a strong airflow, the aerodynamics forces alter the characteristics of these natural modes. Flutter will happen if a positive feedback occurs between the natural vibration and the aerodynamic forces. If the energy extracted from the airflow is larger than the natural damping of the system, the level of vibration increases leading to instability. Flutter can occur on any structure exposed to aerodynamic forces. One famous example is the collapse of the Tacoma Narrows Bridge in the USA in 1940.

An illustration of the flutter phenomenon is given by Fig. 1 which depicts a typical flutter case on airplanes. It results from the coupling between the bending mode and the torsional mode of a wing. If, for some flight condition, these modes have similar frequencies and in-phase oscillations, then the torsion of the wing induces variations on the lift caused by the variations of the angle of attack. When these oscillations on the lift are in phase with the wing bending mode, they amplify the amplitude of the oscillations of this mode and flutter occurs.

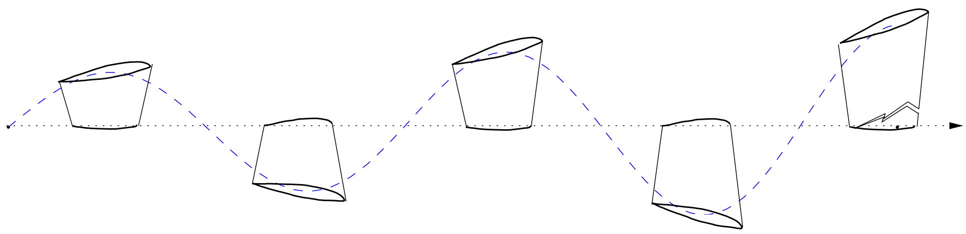

Fig. 1. Illustration of the flutter phenomenon

The physical modeling of the aeroelastic behaviour of an object is quite involved. It is based on the modeling of the structural dynamics and of the unsteady aerodynamic effects. For complex systems such as an aircraft, an exact modeling of every aspect of the structure in every flight conditions is not possible. Detailed testing is the only way to guarantee that an aircraft is free of flutter.

2.2 Requirements for aircraft certification

Airworthiness certification can only be granted by the civil aviation authorities after the stability of the aeroelastic modes is guaranteed throughout the flight domain of the aircraft. The flight domain defines the conditions in terms of altitude, speed in which an aircraft is designed to fly. To be more precise, the weight of the aircraft and the weight distribution on the airframe (fill levels of the various fuel tanks, position of the payload) must also be taken into account.

Fig. 2 illustrates a typical flight domain of a civilian transportation aircraft as a function of speed and altitude. The critical part for flutter analysis is the high speed border of this domain. One can in fact distinguish three limits:

- The *maximum operating* limit depicted by the solid red line. This limit is defined by the speed limit V_{MO} and the Mach number limit M_{MO}. This boundary delimits the speeds that can be used in normal flight conditions.
- The *maximum design* limit indicated by the dashed red line which correspond to the *dive* speed V_{D} and the *dive* Mach number limit M_{D}. These quantities represent the ultimate speeds an aircraft can fly. They can only be reached in extremal flight conditions such as danger avoidance. This peripheral flight domain is also explored during the flutter testing campaign. As sustained flight is not always possible at these speeds, the pilots have to resort to dives to test the aircraft.

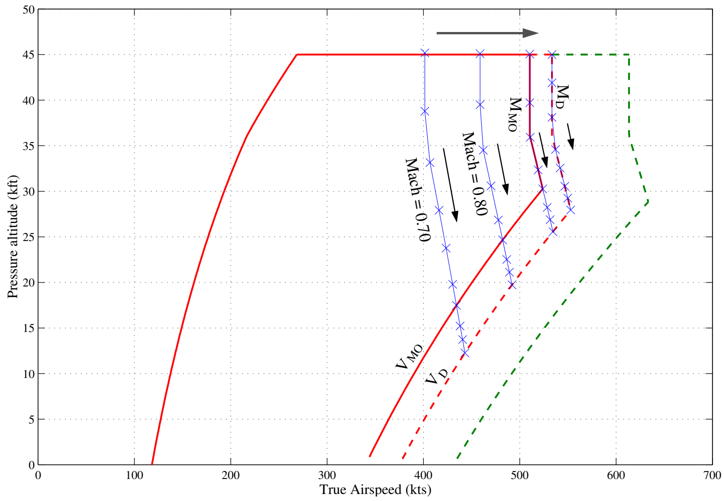

Fig. 2. Flight domain of an aircraft

- the *extended* flight domain indicated by the dashed green line. The delimiting speeds of this domain are specified by the certification rules as being 15 % higher than the ones of the maximum design domain. The behaviour of the aircraft in these flight conditions is only accessible through computation.

The certification requires that the aircraft manufacturer demonstrate by flight testing that the aircraft is exempt from flutter in the whole *maximum design domain*. It should also be demonstrated by computation that no flutter can occur in the *extended flight domain*. This requirement is fulfilled by using physical models updated by flight test data.

So the primary goal of flight tests is to gather data for an off-line analysis in order to write the certification file. However, flutter testing is hazardous because one must fly sometimes close to the actual flutter speed which is in fact not known. The aeroelastic stability may also change abruptly with only a few knots change in airspeed. In order to prevent any flutter advent while the aircraft is on test, a specific testing procedure must be used and an appropriate surveillance of the modes must be carried out *on-line*.

2.3 Flutter surveillance procedure

Current flight tests are composed of several series of tests performed at *stabilized test points* that is to say points where the aircraft is stabilized at a constant speed and a constant altitude. These test points are symbolized by blue x-marks in Fig. 2. Each series of tests is performed at a constant Mach number. As flutter likelihood increases with airspeed, these points are explored in increasing order of speed. Several hundred of test points are analyzed for a new aircraft.

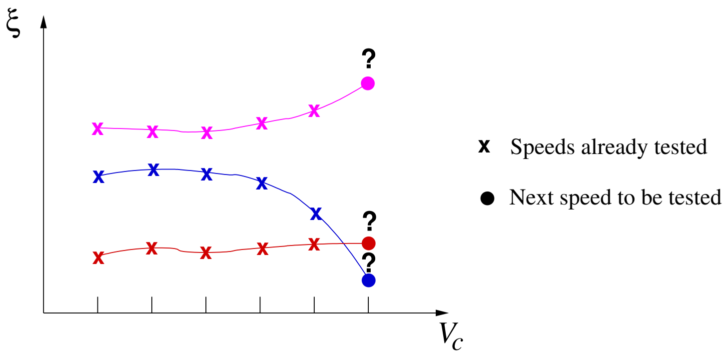

Fig. 3. Extrapolation of damping ratios ξ

At each of these points, several tests are performed by applying excitations to the aircraft structure. The measurements of the aircraft response are transmitted in real time by telemetry to the ground test center where the mode damping ratios are estimated. As illustrated in Fig. 3, the damping estimates obtained at each stabilized test point establish a trend as a function of airspeed which is used to evaluate the stability of the next higher airspeed test point and to clear the airplane to this point.

The excitation are performed by supplying through a specific device excitation signals into the actuators of the control surface of the aircraft. Two types of excitation signal are now used : sine-sweeps and pulse tests. Though these latter tests provide less accurate mode estimates, they are more and more used because of their much shorter duration[1] which leads to a substantial reduction of the duration of flight tests.

2.4 Specifications for processing methods

The methods currently used for flight data processing are essentially *system identification methods* associated with pre-processing techniques such as transfer function estimation. The aeroelastic behaviour of the airplane is supposed to be linear. The estimated modes and their damping ratios are readily derived from the identified systems.

The flight test conditions are not quite favorable to an accurate identification. Firstly, as the aircraft operates in operational conditions, the measurements are affected by the ambient noise due to the airflow around the aircraft. Sometimes, the data are also corrupted by air turbulence when the aircraft encounters wind gusts. Secondly, the excitations by the control surfaces are limited in amplitude, frequency and position. Therefore many of the structural modes are not excited efficiently. Though the algorithms should operate in rather adverse conditions, they must also comply with unusual and severe requirements. We mention here three main requirements.

First of all , the algorithms must operate in a *near real-time manner* because the aircraft crew is awaiting the clearance for the next test point. It must be mentioned that about one thousand identification operations are necessary for the certification of a new aircraft. This also claims for a high processing efficiency.

The second demanding requirement is that the identification algorithms should be *fully automatic*. Of course, this is also in favour of an improved efficiency. But the main reason is actually an ergonomic one. The task of the ground operator is to monitor the safety of the flight. For test point near the flutter speed, the ambiance in the test center can be quite tense. It is not conceivable in such stressful conditions that the operator should shares its attention and analysis capabilities on any other task (such as extracting modes from a stabilization diagram for instance).

The results of the identification should also be *reliable* so that the test series underway should not be stopped unduly by incorrectly low damping estimates. On the other hand, the flutter onset should of course not happened unnoticed.

2.5 Current operational methods

Up until a few years ago, the excitation device used at Airbus could only generate a single signal. Several tests had then to be performed at each test point of the flight domain in order to properly excite the various modes of the structure. The associated identification method is based on a SIMO (Single-Input Multiple-Output) model described by its transfer function. The identification algorithm is an iterative non-linear fitting method which estimates the coefficients of the transfer function. This approach is described in (Vacher and Bucharles, 2006).

A new excitation device is available at Airbus which allows to supply concurrently several signals to several control surfaces on the aircraft. This system enables a great improvement of flutter testing since the various modes of the aircraft can be excited in a single test at each test point thereby reducing the duration of flight tests. Appropriate in-operation MIMO (Multiple-Input Multiple-Output) algorithms are under development.

[1] About 10 s as compared to 2 min for a sine-sweep test.

3 Future orientation for flutter testing

This part of the paper concerns a new testing procedure that was devised in the FliTE2 project. Two possible approaches for flutter surveillance methods are considered : a mode tracking approach and a detection approach.

3.1 New testing procedure

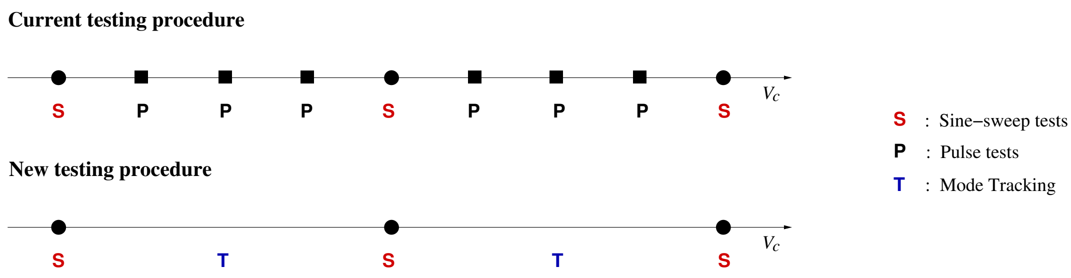

Fig. 4. New procedure for flutter testing

As abovementioned, flutter testing is based on sine-sweep tests interspersed with several pulse tests. This practise is illustrated in the upper part of Fig. 4. It has however two main drawbacks. First it is extremely time consuming since the aircraft has to be stabilized at specific test points, the test have to be performed, the data processed and the results analyzed by the operator. The other weakness of this procedure is that flutter can appear in the acceleration phase between two test points where no monitoring of the aircraft stability is performed.

The idea of the new testing procedure illustrated by the lower part of figure 4 is to replace the intermediate pulse tests by a *uniformly accelerated* phase where the stability of the aircraft would be monitored continuously. This procedure eliminates the most hazardous part of flight flutter testing. It will also lead to a substantial reduction of the overall duration of flight tests.

For a precise and timely detection of any impending instability, the aircraft structure must be excited continuously during the acceleration phase. Several signals can be considered for that purpose: pulse series, sine-sweep, multi-sine, ... The sequence of excitation applied to the aircraft is depicted in the upper part of Fig. 5.

The surveillance algorithms should comply with similar specifications as those described in section 2.4, namely : automatic functioning, reliability of the results. But the emphasis is here on the real-time aspect since the processing algorithms should produce results at a specified rate (at least every second) in the course of the acceleration phase. Moreover these results should have as little delay as possible compared to the actual system evolution.

3.2 Surveillance by mode tracking

The first type of processing one can consider is to track in real-time the evolution of the modes during the accelerated phase. This approach is illustrated in the lower part of Fig. 5. At the initial test point, identified modes are available based on the processing of the sine-sweep test. They are indicated by red x-marks on the figure. These mode estimates can be used to initialize the mode tracking procedure used in the acceleration phase. The results of this procedure can be viewed as an improved version of the mode extrapolation depicted in Fig. 3.

For this approach, reliable confidence intervals are highly desirable for several reasons. First of all, the accuracy of the damping is necessary to evaluate the proximity to flutter. The other reason is that the acceleration could be stopped and a test point at an intermediate stabilized speed could be performed in case of a degradation of the accuracy of the mode tracking. Finally, one could contemplate to modulate the value of the acceleration based on the variation of the tracking accuracy.

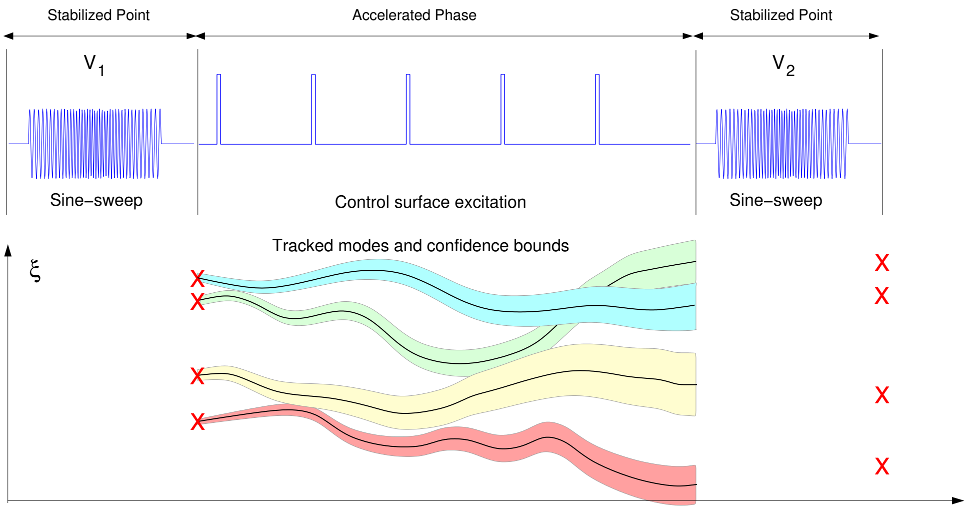

Fig. 5. Mode tracking approach

3.3 On-line flutter onset detection

Instead of estimating the modes, one may consider to provide the operator with a real-time indicator that would directly signal the imminence of flutter. Anyhow such an direct approach does not appear realistic.

First of all the risk of flutter occurrence does not solely depend on quantities such as the value of the smallest damping ratio. It also greatly relies on the technical expertise of the operator which takes into account the physical phenomenons and the nature of each mode. His analysis will also be guided by all the previous events of the flight. Therefore the development of an automatic flutter detection tool appears difficult and would probably be insufficient to guarantee the level of safety required for flight tests.

What could be developed is a *flutter forewarning tool* that would detect specific phenomenons that might indicate a tendency towards flutter. The purpose of this tool would be to call for the operator's attention so that he analyze more precisely the situation and state about the risk of flutter.

It must also be underlined that the monitoring of the least damped mode is not sufficient since a large and sudden decrease of the damping of a heavily damped mode could also be threatening. A more relevant indicator of flutter tendency is probably the value of the *greatest relative decrease* of all the damping ratios.

4 Conclusion

The new procedure proposed in this paper for flutter surveillance is very challenging. Summarized in simple terms, it addresses processing methods related to *multiple-input multiple-output time-variant* systems tested in *operational conditions* and subject to *moderately efficient* excitations. These methods should operate in *real-time*, *entirely automatically* and produce *delay-free* results.

The feasibility of the new flutter testing approach is highly conditioned by the availability of appropriate and high-performance algorithms. Another challenging aspect which is more especially thorny for detection methods concerns the validation of these algorithms in real flight situations.

References

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