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Towards Faster and Safer Flight Flutter Testing

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Abstract

The current state of the art of flight flutter testing is reviewed, and areas where this part of the certification procedure could be improved are discussed. It is argued that the key towards speeding up the flight flutter test procedure, and also to reduce costs, is to reduce the number of flight test points that are required as part of the test clearance programme. To achieve this aim, the entire modelling and testing procedure needs to be improved, particularly with respect to non-linearities. Non-linear aeroelastic phenomena will then be able to be predicted more accurately. Current work in a number of relevant technologies is considered in relation to flight flutter testing. Suggestions are made as to how these aspects could be improved in order to speed up and reduce the cost of flight flutter testing, while maintaining, if not improving, the levels of safety.

1 Introduction

Flutter is potentially the most disastrous of all aeroelastic phenomena and there have been many instances of structural failure from the resulting unstable oscillations [1,2]. Although the first recorded incident was the Handley Page O/400 bomber in 1916, it was not until the mid 1930s that Von Schlippe introduced the concept of a dedicated flight flutter test. Since then, flight flutter testing [3,4] has matured to become a critical stage in the certification process, see figure 1, providing the final validation of the analytical predictions. All aircraft must be demonstrated to be flutter free throughout the entire flight envelope, plus an additional safety margin. A similar process must also be undertaken for the clearance of new types, or combinations, of stores on military aircraft.

The classical approach to flutter testing has changed little over the past half century and, as can be seen in figure 2, systematically expands the flight envelope for increasing speeds over a range of altitudes. At each flight test point, three separate procedures are performed:

1. The aircraft is excited in some manner and the vibration response measured.
2. The data are curve-fitted using system identification methods and the modal parameters estimated.
3. The decision is made to progress to the next flight test point.

There have been 3 major international meetings held to discuss the progress of flight flutter testing, in 1958[5], 1975[6] and 1995[7]. The major technical developments that have had greatest influence on the test procedure are shown in figure 3. In essence, the basic test philosophy had been developed by the time of the first meeting, the second meeting demonstrated the influence of new computational and other test hardware. The third meeting described advances in analytical methods, new forms of excitation devices and consideration of aeroservoelastic effects. Despite these advances, the basic procedure has remained the same [87,88].

Flight flutter testing is very expensive, time consuming, and often undertaken at a time critical part of an aircraft's development programme. The design flight envelope must be cleared as swiftly as possible so that the rest of the flight testing (systems, etc.) may be completed. However, at no time must safety be compromised. Compared to ground testing, it is often difficult to excite the aircraft with an adequate amount of energy, resulting in data with

poor signal / noise ratios due to atmospheric turbulence corrupting the data. Consequently, the quality of the resulting curve-fits becomes worse, leading to less confidence in the estimated parameters and thus the speed increments between flight test points must be relatively small. The number of flight test points considered is often large. Although the test hardware, computational equipment and analysis techniques used for flight flutter testing have improved with time, aircraft have also become progressively more complex in construction, geometry, flexibility and aerodynamic improvements have led to thinner wings. Also, the influence of non-linear effects is becoming greater although the industry bases most of its analysis on linear aerodynamic and structural models that cannot predict such phenomena as Limit Cycle Oscillations (LCO). Consequently, no reduction in the time required to clear the flight flutter envelope has materialised despite the considerable improvements in technology. Meanwhile, costs have increased dramatically. Henshaw, McKiernon and Mairs [8] state that 75% of effort for flutter clearance is in the modelling and analysis stage, and this results in 25% of the costs. The other 25% of the total effort is devoted to the validation and qualification phases with an associated 75% of the total cost.

In this paper, the current state of the art of the key elements that make up flight flutter testing and also aeroelastic computational modelling and prediction, structural and control modelling, and ground vibration testing, is reviewed. Suggestions are made as to how recent advances in a range of research areas could be used to speed up the whole flight flutter test process and reduce costs whilst still keeping, if not improving, the levels of safety.

2. The Changing Nature of Aircraft Design and Its Effect on Flight Flutter Testing

Recent aircraft designs have tended to differ in a number of significant ways from the designs of, say, 20 years ago. Airframe structures are more flexible with less damping, primarily through the use on modern construction techniques such as use of composites and diffusion bonded structures. The application of structural optimisation methods to optimise the structure with minimum mass has led to designs with far less excess structure than before. The design of aerodynamic surfaces has become more advanced leading to thinner wings and more complex aerodynamic shapes. The complexity of flight control system technology has also developed, leading to a far greater variety and number of aeroservoelastic cases that must be considered [129,132]. Likewise, the use of new technologies such as stealth has led not only to different types of aeroelastic problem, but also a dramatic increase in the number of flutter cases that need to be considered. Further changes in aircraft design will follow, for instance there are a number of research programmes [9-11] world-wide investigating the use of aeroelastic behaviour as a positive benefit rather than as a problem that requires a stiff, heavy structure to reduce its effect.

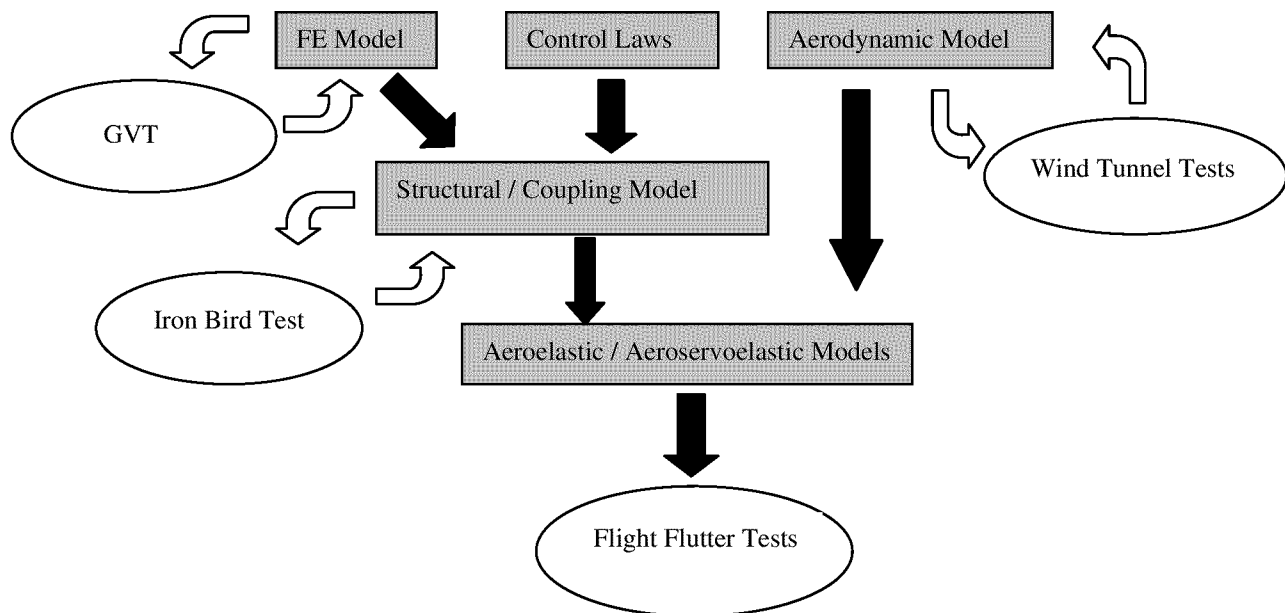


Figure 1. Aircraft Certification Procedure.

These fundamental changes in aircraft design and manufacture have increased the importance of non-linear aeroelastic phenomena [12-14]. The non-linearities manifest themselves via structural (freeplay, stiffening effects, large displacement effects [15]), aerodynamic (transonic effects) and control (time delays, non-linear control laws [16]) mechanisms. One of the key phenomenon that needs to be considered is Limit Cycle Oscillations (LCO). Although not immediately catastrophic, unlike flutter, LCO can be thought of as “only” a fatigue or weapon aiming problem. However, in terms of the prediction of aircraft aeroelastic behaviour, and in particular flight flutter testing, such non-linear phenomena cause significant problems [113]. The vast majority of aeroelastic modelling and flutter clearance is undertaken using linear methods, and these techniques cannot predict the occurrence of non-linear phenomena. Consequently, there is a danger of unforeseen non-linear aeroelastic effects occurring during a flutter test which, at best, cause a significant delay in the flutter clearance and, at worst, can cause an “incident” to occur [114]. A good example of this is the prediction of LCOs occurring when different stores combinations are used on military aircraft; a large amount of flight testing is required to establish the safe flight envelope as there is no efficient predictive alternative. [115,116]

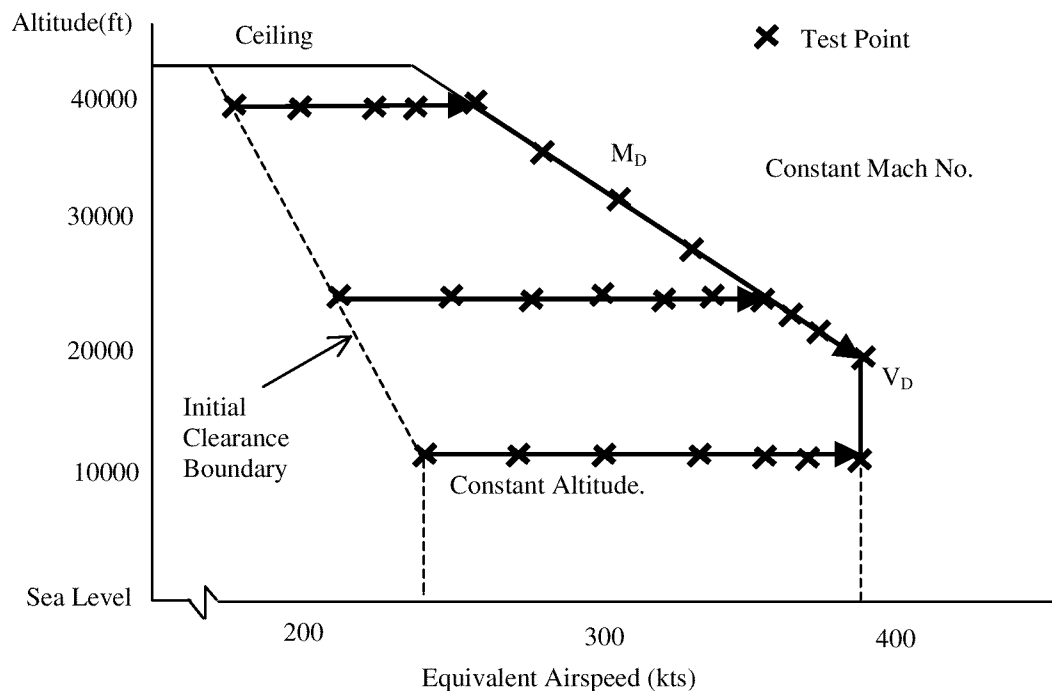


Figure 2. Typical Flight Clearance Envelope

Hardware	Telemetry	Analogue Computer	Digital Computer		
Excitation	Inertial Exciters	Aerodynamic Vanes	FCS		Slotted Rotating Vane
Analysis Methods	Spectral Plotting	Flutter Margin	Fast Fourier Transform	Advanced System Identification Algorithms	μ Method time/frequency methods
Processing of Data	By Hand		Automated Processing	Interactive Processing	
	1950s	1960s	1970s	1980s	1990s

Figure 3. Major Advances in Flight Flutter Testing Methodology

3. Future Developments in Flight Flutter Testing

The last decade has seen a dramatic rise in the interest in modelling and prediction of non-linear aeroelastic effects that can arise due to structural, aerodynamic and control non-linearities. There has also been much interest in identifying non-linear structural models and also predicting flutter boundaries using coupled CFD / structures codes. Other work has considered the analysis of measured flight test data in order to determine flutter boundaries. However, these new developments have not found their way, as yet, to becoming standard use in industry and there is still an overriding reliance upon linear models.

The goal of “Certification by Analysis” has much merit, although this author is horrified at the idea of totally eliminating experimental testing altogether. In respect to flight flutter testing, it is foreseen that a certain amount of testing on the ground and in the air will have to remain. Reductions in both the time and cost of flutter clearance will be achieved by decreasing the number of test flights that are required. This goal can only be achieved by developing more accurate aeroelastic models that can be partially achieved by deducing more information from the data obtained during the ground tests and also during the flight test. The inclusion of more non-linear effects than are currently used will be particularly important along with consideration of the variation in aeroelastic behaviour across aircraft fleets and the effects of ageing. With this in mind, the following sections review the current status of all aspects of the certification process, from aeroelastic modelling through to the flight flutter test itself, in order to examine where possible advances can be made.

3.1 Computational Aeroelasticity

The past decade has seen a significant amount of effort [17-19,83,84] devoted towards the numerical solution of transonic aeroelastic phenomena, not only in the prediction of transonic dip effects but also towards that of LCO. Euler and Navier-Stokes schemes have been both weakly and strongly coupled with structural FE models. Much work has been directed towards the consequences of dealing with two separate meshes, one fluid and the other structural. These approaches are a major advance compared to the linear doublet / vortex lattice types of approach that is still widely used throughout industry and enable non-linear aerodynamic effects to be modelled [82]. Results show that in order to capture all of the physics of non-linear aeroelastic systems in the transonic regime (i.e. the displacements rather than just the frequency of the LCO) very sophisticated models need to be used. The researchers in this field are to be applauded for the development of numerous test cases [20,70] that act as benchmarks used to compare different approaches.

Despite the continual improvements in computational speed and memory, we are still many years, if not decades, from achieving the goal of computing every conceivable case in a practical time scale. Rather than performing a simulation clearance as opposed to flight testing, other techniques should be used to show where in the flight envelope such accurate simulations are needed. Current implementations tend to concentrate upon the non-linear aerodynamic aspects and there is a need to consider the interaction of non-linear structural elements and control systems [85].

3.2 Wind Tunnel Testing

Wind tunnel testing is often used for new configurations in order to obtain aerodynamic data, particularly in the transonic regime [72,79-81,75,76] in support of the CFD calculations [21], particularly in regimes such as buffet where accurate prediction is rather problematic, and also to correct simpler aerodynamic models. There are various areas of uncertainty when performing such tests, for instance: the constraint effects of the tunnel walls and boundary layer, interference effects of the model support, tunnel blockage effects and scaling issues resulting from testing at Reynolds numbers much less than those achieved in real flight. CFD calculations can be used to provide corrections for the wind tunnel effects [74].

Wind tunnel testing is very expensive, both in the construction of scaled models and the use of transonic wind tunnels. Effort is required in order to make the procedure more efficient, through the use of non-contact measurement approaches and simpler models. There is a need to support some of the other technical topics

discussed there through the provision of more benchmark test cases, particularly of aeroelastic models, and also tests where the structure itself is non-linear [73,77,78].

3.3 Structural Modelling

A vast amount of experience has been gained [22] in the use of Finite Element (FE) models for the prediction of structural behaviour although there are still concerns regarding the accuracy of predictions of ultimate loads for static behaviour. As regards dynamic calculations, the FE method has gradually replaced the “stick” models traditionally used by the aerospace industry. A limitation is that the majority of modelling is based upon linear elements, and much work is required to reliably include non-linearities such as joints into structural models. Part of this process will rely on accurate “updating” methods that adjust (i.e. correct) the FE model based upon vibration testing results. Although much work has been devoted to updating methodologies over the past two decades, there are still serious issues in the applicability to real size structures. A recent Garteau exercise [23,24] showed that much progress has been made, although the structures considered are still on a laboratory scale.

A further important issue with structural modelling is that of damping. For many years it has been assumed that it is acceptable to use proportional damping, however, this is not always the case in real structures even if they behave linearly. It can be shown that the proportional damping assumption can cause significant inaccuracies in dynamic response calculations [25], and this will in turn lead to inaccuracies in the aeroelastic calculations where damping is a very important parameter. The damping also has an important contribution to the magnitude and phase of active control feedback [16]. More work is required towards the inclusion of accurate damping models, initially in the measurement and modelling of non-proportional damping, and then non-linear damping.

3.4 Ground Vibration Testing

The standard approach for ground vibration testing in the aerospace industry has not changed a great deal over the past 40 or so years. Traditionally a multi-shaker force appropriation (phase resonance) approach [26,100-102] has been used to excite each mode individually, which enables immediate comparison with the FE model via direct measurement of the natural frequency, mode shape and generalised mass. By exciting around the mode the damping ratio can also be measured. The original manual approach has been replaced with automated procedures. Although most of the modal analysis community tends to use phase separation methods as they are much quicker and easier to implement, these methods are not so commonly used in the aerospace industry as the resulting complex modes are difficult to compare with the FE normal modes.

There is a need to advance the test methodology to gain further information about any structural non-linearities that may be present in the structure. It is required to determine whether non-linearities exist, what type they are, and whereabouts on the structure they can be found. Much work has been devoted [27] to the identification of non-linear structures, but this has resulted in a wide range of different models that have varying degrees of usefulness as regards to the resulting FE models. Also, most experimental validations of these techniques have only been undertaken on laboratory structures containing a few modes. One very promising approach [28,71] is to identify any non-proportional damping and non-linearities as an addition to the usual modal model using the so-called resonant decay method. By using a modal approach it is possible separate modes in terms of whether they have linear or non-linear characteristics and to consider groups of modes that are coupled either due to non-proportional damping or by non-linearities.

3.5 Aeroelastic Modelling

Having established the linear structural and unsteady aerodynamic models, it has been traditional to use one of a number of frequency matching techniques in order to determine the flutter condition, frequency and associated modes. The inclusion of structural and aerodynamic non-linearities does away with the ability to simply predict the flutter point, and there are at present not many techniques that can be used to predict behaviour such as LCO without resorting to numerical simulation of every test point. The harmonic balance method [67] has been used to predict LCO behaviour for non-linear structural cases such as freeplay but there are limits as to the effectiveness

of this approach. There has been much work on characterising non-linear aeroelastic behaviour, and this now needs to be extended to larger systems [118-128].

3.6 Aeroservoelastic Modelling

There are typically many control laws in any flight control system, with the inclusion of notch filters to eliminate any undesirable behaviour. The resulting transfer function contain discrete non-linearities, not only from the different laws, but also from time delays due to signal processing constraints[16, 29-31,37]. It is usual to model these non-linearities with linearised approximations, which enable flutter calculations to be made in a similar manner to a non-FCS aircraft. The number of failure cases that need to be considered also increases dramatically when a FCS is involved [131].

In order to achieve a greater accuracy in aeroservoelastic modelling that will no doubt be needed in the future, the use of non-linear models will have to be employed. As with aeroelastic testing, there is a danger that a large amount of simulation will be required to investigate every case, particularly as the non-linearities will be of a discrete nature and will include switching between a large number of different laws.

3.7 Structural Coupling Tests

For aircraft with active control systems, the coupling of the structure and the flight control must be tested [16,30-36,130] to see how well the linearised laws compare with reality. The procedure consists of frequency sweep excitation of the flight control system, and also the application of loads on the control surfaces with open and closed loop control system. Although there are no airforces present, such tests are extremely important, as this is the only chance to test whether there are coupling problems that could have disastrous consequences. This is one testing element of the certification procedure that is not seen as changing dramatically.

3.8 Reduced Order Modelling

Despite the dramatic increases in computational power, typical aeroelastic models are very large if non-linearities are included, even if considered in a modal sense. Consequently, a number of researchers are investigating means of developing a reduced order modelling capability that will enable predictions to be made using much smaller models. Such approaches will enable a wide range of design cases to be considered efficiently in order to determine the critical cases and also to perform parameter design studies. Outputs from full aeroelastic models are then curve-fitted in order to produce the reduced order model [103,106,107]. Examples include curve fitting impulse responses [38] to produce a linearised model of the aerodynamic state space model [108-112], and fitting of a Volterra series to determine the non-linear effects [39]. Many investigations have considered the POD approach[111].

Other work has examined the use of Normal Form Theory to model aeroelastic systems containing non-linear structural and aerodynamic effects [40,41,104,105]. This approach enables the full non-linear behaviour to be predicted, including the shape of the LCO. There has to be a compromise between including enough non-linear terms to model the behaviour accurately while reducing the model to a small enough size to allow the normal forms to be computed.

3.9 Excitation Signals and Devices.

One of the key difficulties with flight flutter testing is the noisy environment that it is performed in. Although there have been many cases where stick raps or simply turbulence has been used as an excitation signal, some form of excitation device must be used if good quality data is to be obtained. It is very difficult to obtain estimates of the modal properties if the data is poor, and this is ever more the case if non-linear identification is attempted. Since the invention of the slotted rotating cylinder flutter vane [42-44] in the early 1990s, no further advances in excitation technology have been made apart from the suggestion of a contra-rotating propeller driven device for stores[133]. When ground testing an aircraft, it is considered better to use multi-shaker technology in

order to excite close difficult modes, so surely multi-exciter technology should be used in flight. A number of issues are raised as to how to achieve this. One possibility is to use a variety of different exciters (inertial masses, fcs, vanes) placed around the aircraft [45,46], or to use a number of aerodynamic vanes for instance attached to combinations of stores. The positioning of both the exciters and transducers should be optimised using theoretical models before starting the test.

The type of excitation signal should also be considered. When the conventional linear or logarithmic chirp (fast swept-sine) excitation is used, the time data between modes is effectively wasted. Some work has been undertaken to develop both chirp [48] and random signals [49,50] that will give consistently good signal noise ratios with effective crest factors. It would be of interest to implement some of these methods on real aircraft in order to see how well the estimated parameters compare to those obtained using more conventional approaches[86]. There is a need to develop a device for applying random signals in flight apart from the fcs.

3.9 Modal Parameter Identification Methods for Flight Flutter Testing

There is a wide range of different modal parameter identification methods [51] that have been used for flight flutter testing in order to identify natural frequencies and damping ratios from the test data. These techniques have varied in sophistication from a simple half power points analysis [44] to multiple input – multiple output maximum likelihood algorithms [52]. The modal filter approach has been the only recent innovation in this area [69]. All these methods have been used in a form that assumes that the system is at a constant flight condition and is linear. Surprisingly it is unusual to make use of the mode shapes [54] which benefits the mode tracking procedures. Also, there has been little consideration [52,53] of the differences between a conventional modal test on the ground and a test performed in flight. The major difference is the presence of significant process noise acting through the aircraft structure in the form of turbulence. This corruption affects the data in a different way compared to that of the small amounts of measurement noise encountered on a ground test. Further work is required to investigate the reported improvements in using parameter estimation methods that take this into account. The use of techniques such as blind signal processing should be investigated to determine whether this is a suitable means of improving the quality of flight test data. In flight non-linear identification should also be considered.

Recent studies have investigated the use of using some form of on-line estimator [55,58,66,86,97-99] to track changes in the modal parameters as the aircraft changes between flight conditions. The current vogue is for time-frequency methods such as wavelets [56,57,64] or short term Fourier transforms [59], however, an on-line time domain method is just as suitable. If it were possible to track accurately on-line frequency and damping estimates, then this would be a key advance in extending the gap between different flight test points. Taking the view that reaching a test point is a good indication that most (but unfortunately not all) flutters will not occur, then an exciter could be used continuously (the methodology does not work so well for turbulent input [60]) to excite the aircraft as the flight envelope is expanded.

An extension of the multi-shaker test is to apply force appropriation in flight. The burst appropriation approach could also be used to identify non-proportional damping and non-linearities.

3.10 Flutter Prediction Based Upon Flutter Test Data

One of the most critical decisions during any flight test programme is the decision to move onto the next flight test point. Traditionally this has been achieved by tracking and extrapolating the damping values and determining whether stability is maintained. Methods such as the flutter margin and the envelope function [61,93] can be employed to use the estimated frequency and damping values to predict the flutter speed. A notable recent development is the use of the μ robustness methodology [62,89,94] to predict the flutter speed, along with methods based upon neural networks [65,91,95,96,117], time domain methods [63,68] and others [90,92]. These approaches can be combined with the on-line identification methods to produce an on-line estimate of the critical speed that again can aid an increased gap between test points.

The above approaches are suitable for the analysis of linear systems, but cannot be used reliably when there are non-linearities of whatever form. Procedures need to be developed to analyse data from the earliest flight test points in order to establish what non-linearities exist and whereabouts on the structure they occur. These non-linear models could then be used to predict points of instability and also non-linear phenomena such as LCO.

4. Discussion

The above analysis shows that there are a number of improvements that can be made so that the amount of flight flutter test points can be reduced. From the aeroelastic (and aeroservoelastic) point of view, we are well on the way towards improving the modelling capability in terms of non-linearities. However, this is only one step in producing a truly predictive capability and there is a requirement to use the CFD methods in an efficient and intelligent manner. Improvements in reduced order modelling are needed so that prediction of LCO and flutter behaviour can be made efficiently. These efficiency gains will enable parameter studies and consideration of all critical cases to be considered. Having defined the critical flight envelope regimes, the CFD methods can be used to explore them in more detail. These improvements in the modelling capability will provide a greater confidence in the aeroelastic predictions and the number of flight test points can be reduced.

As regards the actual test, further improvements need to be made in the type of excitation signals, along with multiple excitation sources, which will improve the noise signal ratios. The possibilities of using more advanced system identification algorithms that account for process noise should be considered, along with on-line identification schemes with continuous excitation signals throughout the flight envelope to allow for constant monitoring of the stability. Methodologies such as the μ robustness method need further examination for the prediction of the flutter speed, along with consideration of the confidence of the estimated parameters. Such approaches will enable bigger steps to be taken between flight test points. Flight test data should be analysed to determine whether there are non-linearities in the data, and the reduced order modelling approaches adapted to produce in-flight estimates of the characteristics of any non-linear behaviour and its whereabouts in the flight envelope.

In order to achieve the savings in flutter test time, greater effort will have to be placed in the analysis part of the certification process. Ground Testing should not be eliminated but enhanced in order to obtain more information, particularly non-linearities. The 75:25:25:75 distribution of effort/cost for analysis/clearance described by Henshaw, McKiernon and Myers [8] will need to change to become something more along the lines of 90:10:10:90. Also, as the number of flight flutter test programmes decreases, along with the number of experienced practitioners, there is a greater need for more comparative studies using benchmark data and discussions / workshops between interested parties e.g. the recently started TTCP activity in flutter testing. To help maintain the level of expertise, another possibility is the development of a “flight flutter test simulator” where the flutter clearance of an aircraft could be undertaken using predefined sets of data which could contain a variety of different problems (noisy data, non-linearities, etc.) It is dangerous to consider reducing the amount of testing whilst reducing the expertise that could determine whether problems were likely to arise during a test programme.

5. Conclusions

The current status of all elements in aeroelastic / aeroservoelastic modelling and flight flutter testing has been reviewed with the aim of determining how flutter testing can be performed in less time and cost while maintaining, if not improving, safety. Modelling capabilities should be improved to include all forms of non-linearity and Ground Testing improved to aid this. Improvements in reduced order modelling will be required in order to make efficient use of the CFD based simulations. Flutter test procedures and analysis should be extended to allow for on-line updating of the stability and also non-linear identification to predict phenomenon such as LCO from the flight data. The world-wide flutter test community should ensure that expertise is not lost through loss of personnel and should strive towards the development of benchmark flight flutter test data sets.

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