Structural Dynamic and Flutter Testing

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ABSTRACT

The current state of the art of dynamic testing in view of Structural Dynamics, Aeroelastic and Aeroservoelastic qualification of Aircraft is reviewed. In particularity the areas where this parts of the certification procedure cloud be improved are discussed. The key to speeding up the clearance test procedure, and also to reduce costs, is to reduce the number of tests, test time and flight test points that are required as part of the clearance programme. To achieve this aim, the entire dynamic modelling, as well as the analytical approach and the testing procedure needs to be optimized, particularly with respect to non-linearity. Non-linear aeroelastic phenomena will then be able to be predicted more accurately. A number of relevant technologies are considered in relation to flight and ground testing. Suggestions are made as how these aspects could be improved in order to speed up and reduce the cost of ground and flight testing, while maintaining the levels of safety.

1.0 INTRODUCTION

Using the Collar triangle of aeroelasticity (Figure 1) which was first published in 1946, aeroelastic flutter is an interaction of unsteady aerodynamic, elastic and inertia forces on structures to produce an unstable oscillation that often occurs in disastrous structural failures. High speed aircraft are most susceptible to flutter, although flutter has recognised at low speed. In principle no speed regime is truly immune from flutter. External store flutter is in most cases lower than clean aircraft flutter and in some cases a new type of oscillation mode, called limit cycle oscillation (LCO) occurs.

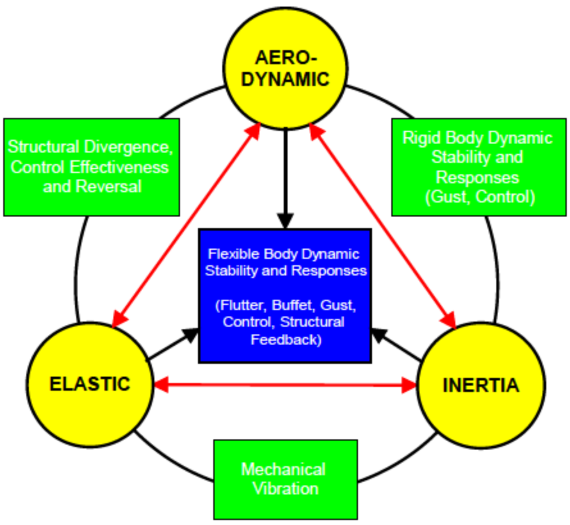

Figure 1: Aeroelastic Triangle.

The first recorded aeroelastic incidence was on a Handley/Page O/400 twin engine biplane aircraft in 1916, but for a long time flutter was not taken into account as certification analysis. In this early time the aircraft was simply flown to the maximum speed to demonstrate the aeroelastic stability of the vehicle. The first systematic flutter test was carried out by von Schlippe in 1934 in Germany. His approach was to excite the aircraft at resonant frequency at higher speed and plot amplitude as a function of airspeed. This idea was applied successfully to German aircraft until a Junkers JU90 crashed due to flutter in 1938.

During the design phase of a modern aircraft the aeroelastic flutter plays a fundamental role. Due to the fly by wire system the advanced digital flight control system for a modern military aircraft is also strongly influenced by aeroservoelastic effects. Aeroservoelasticity (Figure 2) or structural mode coupling is the interaction of structural dynamics, unsteady aerodynamics and the flight control system dynamics including the servo actuators of the control surfaces. The flexible aircraft behaviour, especially for artificial unstable aircraft configurations with outer wing missiles, tip pods and heavy under wing stores and tanks has significant effects on the structure and flight control system. The signals of the Aircraft Motion Sensor Unit (AMSU) - the gyro platform - contain besides the necessary information of rigid aircraft rates and accelerations also flexible aircraft rates and accelerations in the frequencies of the aircraft elastic modes. The 'flexible' aircraft rates and accelerations measured by the inertia measuring unit (IMU) are passed through the flight control system control paths, they are multiplied by the FCS gains and FCS filters and inserted in the control surface actuator input which then drives the controls in the frequencies of the elastic modes of the aircraft. The flexible aircraft is excited by the high frequency control deflections and might also experience aeroservoelastic instabilities, i.e. flutter or limit cycle oscillations may occur, and dynamic load and fatigue load problems can arise. The FCS design therefore has to minimize all structural coupling effects through the available means like optimum sensor positioning, notch filtering and additional active control.

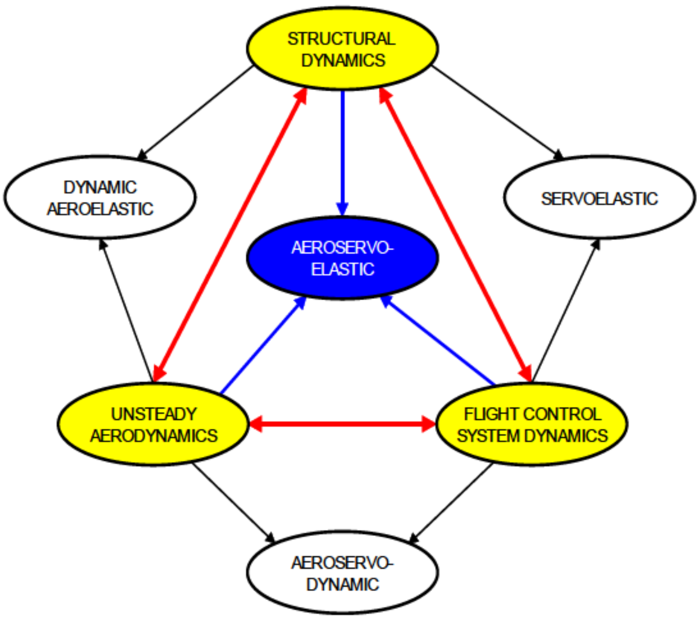

Figure 2: Aeroservoelastic Triangle.

This lecture discusses a historical overview of the use of ground and flight testing for the proof of structural integrity. In particular the tests will be described in the view of structural dynamics. These means that manly dynamics test will be discussed. In particular the development of Ground Vibration Testing, flight flutter testing, the development of excitation systems, instrumentation systems and analytical methods to improve the flight flutter testing will be discussed.

2.0 ANALYTICAL METHODS USED FOR PROOF OF STRUCTURAL INTEGRITY

2.1 Structural Modelling

There are many finite element methods available to predict the structural behaviour. It should be mentioned that the current practice to use one finite element model for all investigation do not satisfy all engineering disciplines. It turned out by using the dynamic models as a subset of the static model; this dynamic model contains a lot of uncertainness in view of dynamic analysis. Using the fine grid system as a master model for static and to reduce this model by dynamic or static condensation a lot of spurious modes appears, which influence the flutter analysis fundamentally. The grid system for the reduced set of structural points must be defined in very early stage of the development. The coupling of the dynamic grid system with the unsteady aerodynamic grid system must be defined before a modal analysis is performed. The model should also include grid points for the updating process, which is required after the ground resonance test. Figure 3 and Figure 4 shows the fine static and coarse dynamic grid.

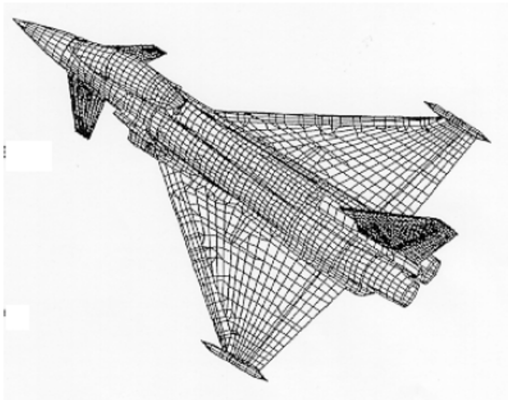

Figure 3: Fine FE-model Grid.

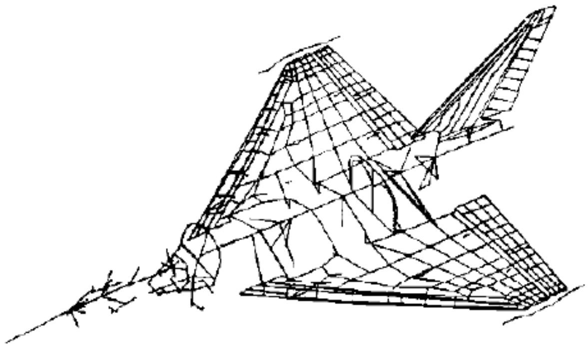

Figure 4: Dynamic Grid points.

For a long time it has been assumed that it is acceptable to introduce proportional damping in dynamic analysis. Tests on structures have revealed that this is not always true on real structures. It has been shown by analysis, that proportional damping predicts inaccurate loads in dynamic response calculations. Aeroelastic prediction is very often influenced by structural dynamic damping results. In many cases the damping values are inaccurate. For instants at aeroservoelastic investigations, the damping influences the magnitude and the phase of the active control feedback and causes many problems in the design of structural filters. More analytical work is therefore required to develop computer codes which are able to consider non proportional or viscose damping terms.

2.2 Model Updating

To improve the analytical analysis an update of the stiffness distribution of the dynamic model with ground resonance test results is required. In the last two decades many analytical methods have been developed for updating, which can be classified as local and global methods. Updating of structural and geometric non-linearities is still a challenge. Most of the Methods do not taking into account the structural damping of the A/C structure. Sensitivity analysis is required to localize the errors in the dynamic modelling. With the results of the sensitivity analysis the model can be checked for robustness about the dynamic analysis and the areas shown of the airframe structure where changes in the model have fundamental effects. Using the above described method of the dynamic model all updating methods run into problems because the dynamic model is not available as finite element model due to the dynamic reduction. To improve the updating process, the quantity and quality of test measurements have to be improved. Methods where non-linearities and structural damping can be considered are required for further investigation.

2.3 Unsteady Aerodynamic Modelling

The unsteady forces used in the dynamic model calculation shall be represented in a conservative manner.

The magnitude (modulus) of the unsteady forces of the flexible modes and of the control surface defection shall be predicted to represent a realistic high value for all Mach numbers and incidences. Since flow separation at higher incidences is leading to alleviation in the motion induced pressure distributions of the flexible modes and of the control surface deflections the introduction of unsteady aerodynamic forces from pure linear theory is regarded to be conservative. Special attention has to be put to transonic effects on the unsteady aerodynamic forces. Since, however, the structural coupling critical conditions which are related to the worst gain condition of the FCS are high incidence conditions, because the FCS gains result from low control surface efficiencies at high incidence, the assumption of linear unsteady subsonic and supersonic aerodynamics derived by linear theory or numerical Euler code calculations in the linear range is believed to be conservative throughout the full flight envelope.

The magnitude for the unsteady aerodynamic forces is sufficient for the design of high frequency elastic mode notch filters, because only a gain margin requirement is requested.

It shall be stated that the unsteady forces must be calculated for a number of reduced frequencies to cover the full frequency range.

For the phase stabilization of low frequency flexible modes like the first wing/fin bending the unsteady aerodynamic phase shall be represented in a conservative manner. A reasonable approach for the phase of the first elastic mode is again the application of linear theory. The augmentation is that at high incidence and combined high FCS gains the aerodynamic damping is increased compared to low incidence from experience found for different wing configurations.

2.4 Aeroelastic Modelling

In most cases the aeroelastic models are linear in structure and unsteady aerodynamic, this will be taken as input data for the flutter analysis. The doublet lattice method is applied for the calculation of the unsteady aerodynamic. This is a very efficient method with adequate results in the linear assumption. For the solution of the flutter equation the powerful p-k method is standard in industry, because an automated tracking of the modes is possible. This is an important requirement for structural optimisation process and for many trend investigations during the development phase. To improve the analysis results to more accuracy the measured damping derived from ground resonance test must be introduced into the calculations separate for each mode. For the introduction of structural non-linearities, such as free play or backlash the harmonic balance or the point transformation is used, but there are limits of this approach. Methods have to be developed to extend the aeroelastic non linearity to larger systems.

2.5 Aeroservoelastic Modelling

Aeroservoelasticity or also called FCS-structural mode coupling is a phenomenon associated with the introduction of a closed loop flight control system into a flexible airframe. The system might be provided to enhance the natural stability of the aircraft, or, to provide artificial stability to a configuration which has been designed to be unstable to achieve the aerodynamic system specification.

For solution of the structural coupling problem, attenuation of the high frequency oscillatory signal introduced into the flight control system by the flexible aircraft motion should be provided and notched, such that the closed loop is stable and degradation of the performance of the flight control system, or damage of the aircraft structure, is avoided.

Therefore an integrated design shall include the derivation of FCS gains, phase advance filters and notch filters to minimize structural coupling in one combined optimization process. The FCS shall be designed to cover the full rigid, flexible aircraft frequency range with respect to aircraft rigid mode and structural mode coupling stability requirements for each control system individual loop for on ground and in flight. The structural coupling influences shall be minimized by FCS notch filters. The FCS shall be designed to be as robust as possible with respect to all possible aircraft configurations and configuration changes, (missiles on, off, tanks on and off, etc.). That includes that all structural coupling changes with configuration should be covered by a constant set of notch filters to avoid system complexity due to configuration switches for different sets of notch filters. In addition any scheduling of notch filters with flight conditions should be avoided in a wide range of the flight envelope but not excluded for critical structural coupling areas. In order to avoid problems in the notch filter design due to non-linear unsteady elastic mode and control surface aerodynamics and non-linear actuator dynamics the elastic mode stability requirements should mainly be based on gain stabilization of the flexible modes. Phase stabilization shall only be applied to low frequency elastic modes in order not to create too complex design and clearance procedures. Phase stabilization of low frequency elastic modes might not be avoided; it is used as tool to meet handling requirements.

The notch filter design can be based upon an analytical model of the aircraft structure including a linear FCS model. The analytical model must however be verified through ground test results both from ground resonance and structural coupling testing and from inflight flutter and structural coupling testing. The model should be updated by the test results for different configurations. Due to restrictions in the accuracy of the analytical model predictions on ground and in flight mainly at high frequency elastic modes where the prediction becomes more and more unrealistic the analytical model data with respect to inertia shall be replaced by on ground measured data. In order to cover all possible sets of aircraft store configurations a selection of critical configuration has to be established by analytical model investigation in advance.

The most critical selected configurations have to be introduced into the design of the structural filters.

The integrated FCS gain, phase advance filter and notch filter design shall cover the full range of stores and fuel states for the absolute worst case of FCS gain for trimmed aircraft conditions and shall also take into account worst gain situations in out of trim conditions.

Figure 5 shows in principal the longitudinal flight control system of a fighter aircraft.

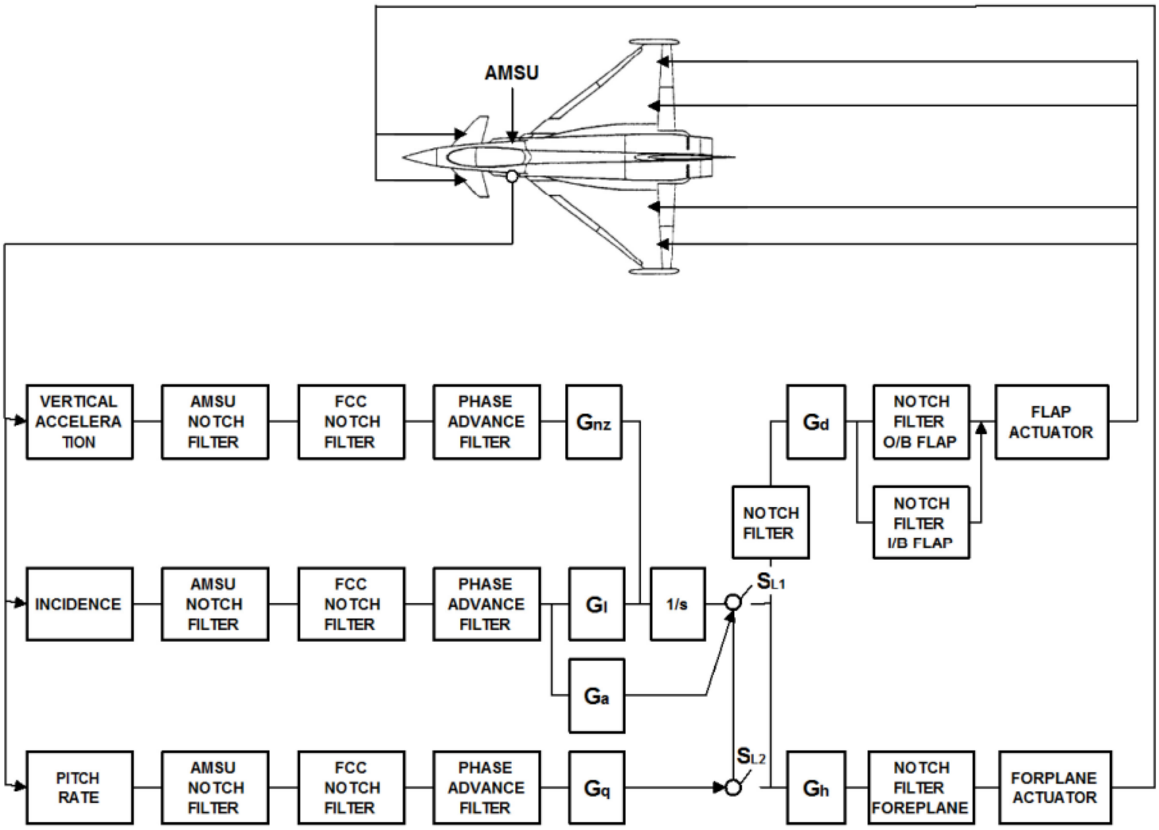

Figure 5: Flow chart of the Longitudinal Control of a fighter type Aircraft.

3.0 TEST TECHNIQUES USED TO PROOF ANALYTICAL METHODS

With the increased emphasis on high performance aircraft the role of structural dynamics in the design and clearance process has become more important. Parameters that improve characteristics such as lower thickness on chord ratio, larger surface areas and higher aspect ratios are driven to near optimum values within the constraints of weight and structural dynamics limitations such as flutter, vibration environment, including acoustics, control surface effectiveness, and buffet response. Because modern combat aircraft features a powerful fly by wire Flight Control System (with Command and Stability Augmentation System) aeroservoelastic analyses and tests had to be performed to avoid adverse coupling of the Flight Control System with the elastic structure of the aircraft. Since the aircraft also carries a tremendous number of external stores on underwing pylons and on fuselage differing in weight and radius of gyration the problem of giving aeroelastic (flutter, gust, buffet...) and aeroservoelastic clearances must be tackled with very careful selection of certain stores to define corner points and read across between the stores. The problem gets more complicated when fuel tanks are considered and flutter and structural coupling free emptying sequences have to be defined. It should also be mentioned that covering the supersonic flight regime almost doubles the analytical and test efforts compared to subsonic aircraft.

The basic for analytical work is a reliable model. In this sense the dynamics testing is most important. Figure 6, shows the structure of dynamics testing on ground and Figure 7 depicts the dynamic testing inflight.

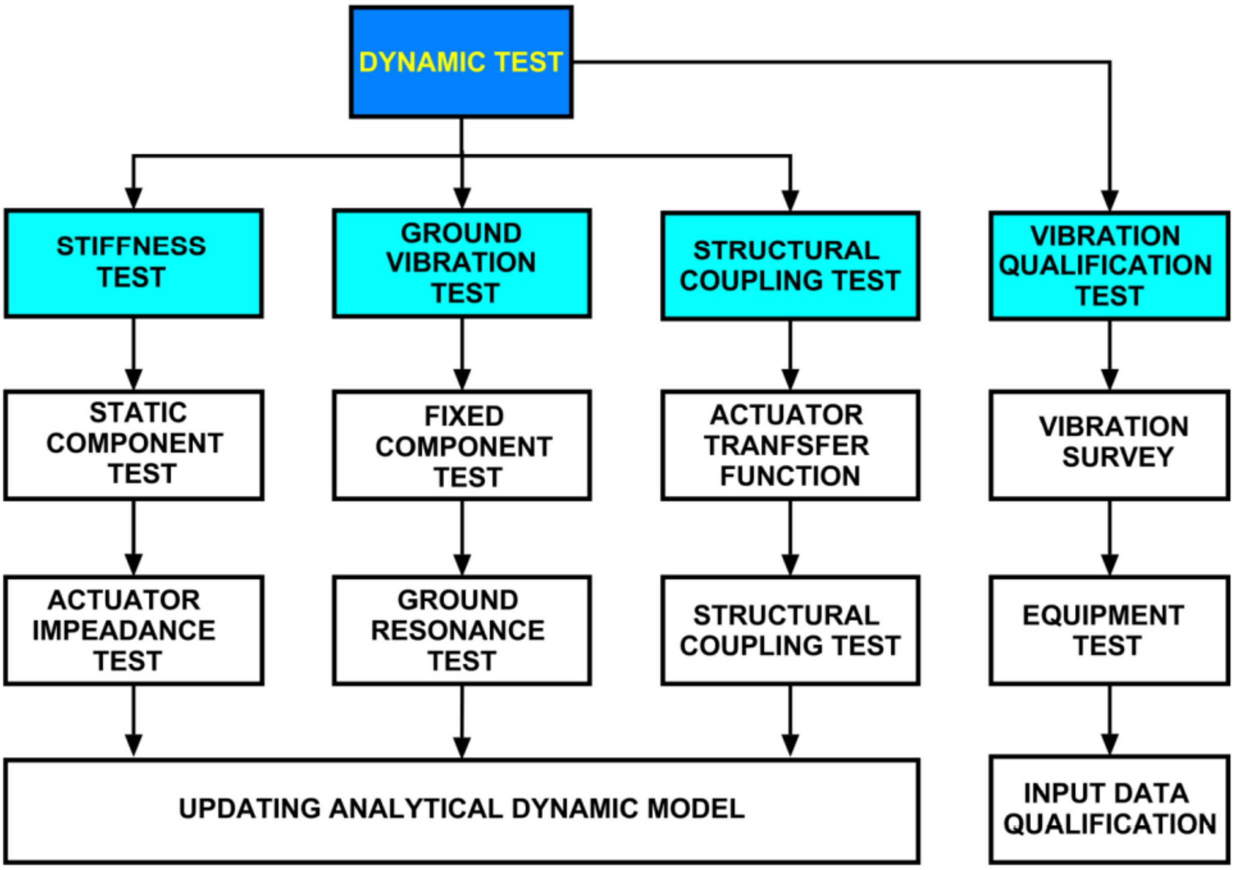

Figure 6: Structural Dynamic Tests on Ground.

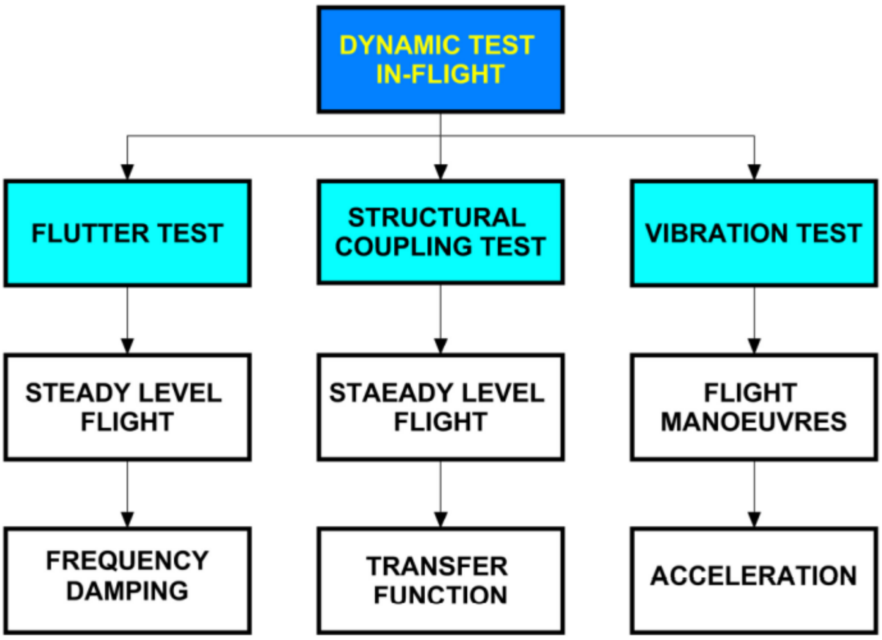

Figure 7: Dynamic Tests in Flight.

3.1 Ground Resonance Test

The ground resonance test is required for updating the mass and stiffness distribution of the dynamic model before first flight. The standard approach for ground vibration testing has not changed over the last decades. A multi shaker force approach (phase resonance technique, also called classical method) will be used to excite each elastic mode of the aircraft structure individually. This method have the big advantages to compare directly the test results with the dynamic model (finite element model) results in terms of frequency, mode shape, generalised mass and generalised damping coefficient. There are many software packages available to use this resonance method automatically with so called indicator functions. The second method also used in aircraft industry is the phase separation methods, which are faster and easier to implement. The disadvantage of the phase separation methods are the complex modes. Which are difficult to compare directly with the FE-model? The complex modes contain the damping of the structure.

There is a need to advance the test methodology to gain information about any structural non-linearities. It is essential to determine if non-linearities exist, and which type of non-linearities on the structure can be found. Useful methods, like harmonic balance will be used to calculate equivalent stiffness values at geometric non-linearities. Also Methods are available to use ground resonance test results for establishing a Finite Element model, which is a very sophisticated tool to create a dynamic model from aircraft, without the basic data of an Aircraft.

The main purpose of ground vibration test (GVT) or Ground resonance test (GRT is GVT including hydraulics on) is to validate the dynamic model and to determine the structural damping coefficients. Here a couple of important questions which have to be discussed before the starting the test procedure:

- How many transducers are necessary?
- Where to place the transducers?
- How many exciters are necessary?
- Where to place the exciters?
- How to tune the exciter forces?
- Which method should be applied (Phase resonance or phase separation method)?

The following step has to perform:

- Resonance search by means of frequency sweeps or indicator function.
- Tuning selected mode frequency.
- Measuring of frequency and mode shapes.
- Linearity check (variation of force).
- Determination of gen. mass (complex power, electr. stiffness) and damping coefficient (decay, complex power, ...).

To measure the elastic modes of the aircraft in flight, the Aircraft will be supported on air springs. In this support the landing gear can be retracted. It must be shown by measurements, that the three rigid body modes (heave, roll and pitch) due to the airspring support, does not couple with the first elastic mode. The criteria are reached if the highest ridged body mode is less than 1/5 of the first elastic mode.

3.2 Dynamic Aircraft Component Tests

Ground resonance tests on rig mounted Aircraft components have been performed to define the vibration behavior and to adjust the mathematical model used in vibration- and dynamic response calculations. Typical examples were GRT on rig mounted vertical tail and wing as well as rig mounted pylons with single and multiple store configuration. Also missiles with launcher and pylon on Aircraft or rig were tested. Beside the measurement of vibration of the pylon with external store stiffness measurements have been performed. Due to a static load which is increased on each step up to a maximum, the displacement of the store can be measured. After maximum load, the load will be reduced in the same steps up to zero. With this method the non-linearities in form of a hysteresis can be measured. The results of these measurements will be used to update the dynamic model.

Figure 8 shows a Ground resonance test with different stores. In the next Figure 9 the support system is shown. Figure 10 depicts a GRT of an aircraft with external stores, excitation on the wing tip pod.

Figure 8: Fixed component Ground Vibration Test with different stores, courtesy of Lockheed Company.

Figure 9: Air spring system used for Ground Resonance Tests.

Figure 10: Mode Excitation on wing tip pod.

Figure 11 depicts the change of the fundamental frequencies of a store with pylon on cantilever component resonance tests with different stores. With increase of mass the pitch mode increases and the lateral mode decreases. After crossing the two frequencies, it can be expected that also the flutter behaviour will be change. Figure 12 shows a component stiffness test on pylon with launcher and missile. The both hydraulic cylinder produce high forces, for the measurements of non-linearities and free play in the system as well as the overall stiffness of the pylon and the attachment stiffness.

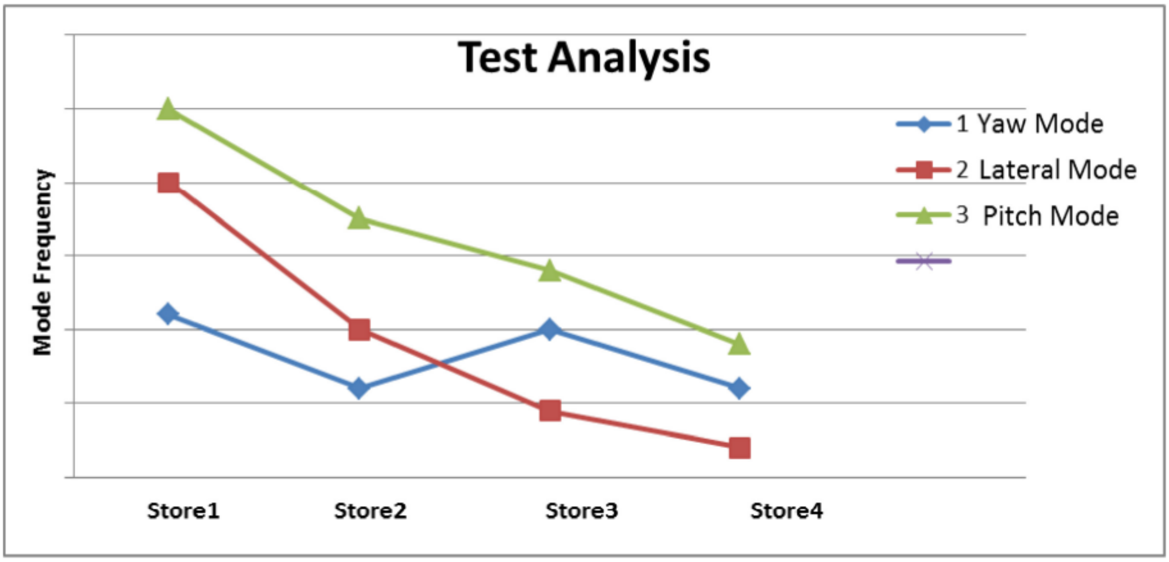

Figure 11: Change of store Modes frequency of different stores.

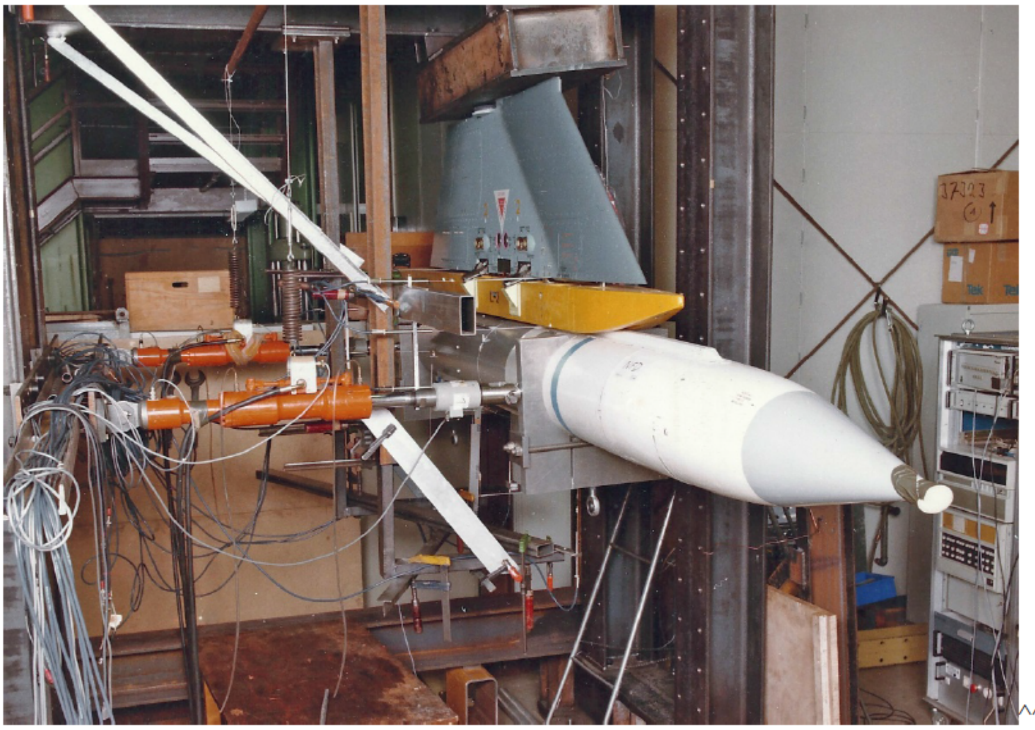

Figure 12: Component Stiffness Test, Missile with Launcher and Pylon.

3.3 Main U/C Drop Test

Wheel spin-up force at landing touchdown bends the U/C backwards. On main U/C this bending is accomplished by leg twisting, since the single wheel is laterally offset from leg. After spring-up, the circumferential tyre force reduces, which initiates both bending and twisting spring-back. At the same time the tyre attains full side-force capability. Therefore, the twisting oscillation spurs a lateral oscillation as well.

Due to the much non-linearity involved –especially with regard to tyre behavior- a comprehensive drop test program has to be performed with heavily instrumented main U/C attached to a center fuselage section, see Figure 13. Approximately 70 drops were required onto a rotating drum, varying "forward speed". A/C mass (including with and without external stores), lift to weight ratio, sink rate, pitch angle, bank angle, yaw angle as well as wheel toe-in angle and different torque links. Tests must be accomplished by computer simulations aiming mainly at dynamic correlation of the load triplet, vertical load, fore and aft load, and lateral load.

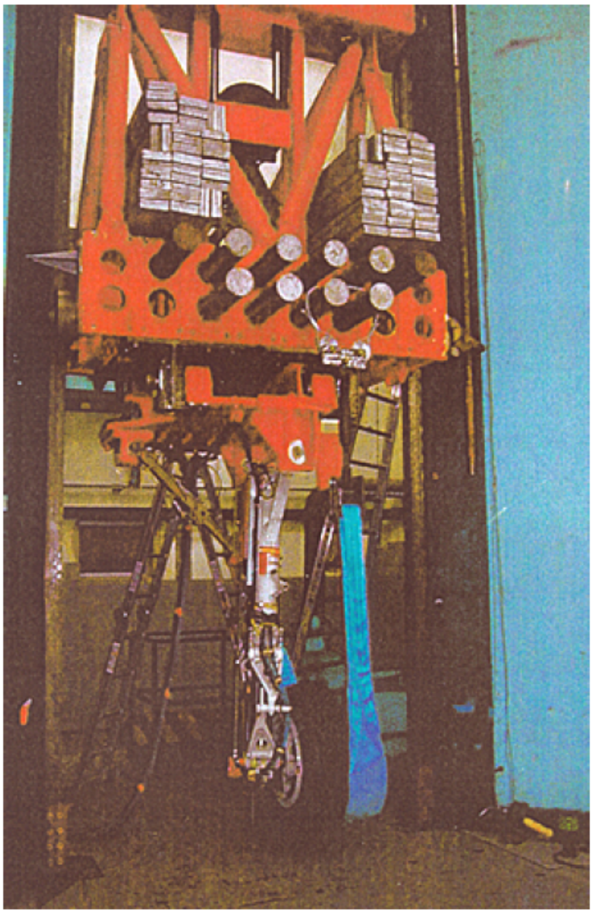

Figure 13: Main Undercarriage Drop Test Setup.

The results of the drop tests will be introduced into a combined undercarriage/aircraft code, which will be used for prediction and recalculation of the U/C flight tests as well as for clearance for military aircraft landing envelope. This program will also be used for repaired runway capability of the aircraft.

3.4 Vibration Qualification of Assembled Stores

Instead of rigid shaker mounted stores rig mounted subsystems of store, ERUs and adapter, Launcher or pylons have been used to simulate reasonable store environment. The test procedure was based on MIL-STD 810, Method 514, Procedure II. Key points of the procedure are the control of store response data in forward and rear store reference plane and direct excitation of the store by means of rod mounted shaker. The shaker attachment outside of the store center of gravity allows for instance also the excitation of important store yaw and pitch modes. Figure 14 is an example of the subsystem test rig close to the mounting condition on the Aircraft. Good test experience has been gained with this test procedure.

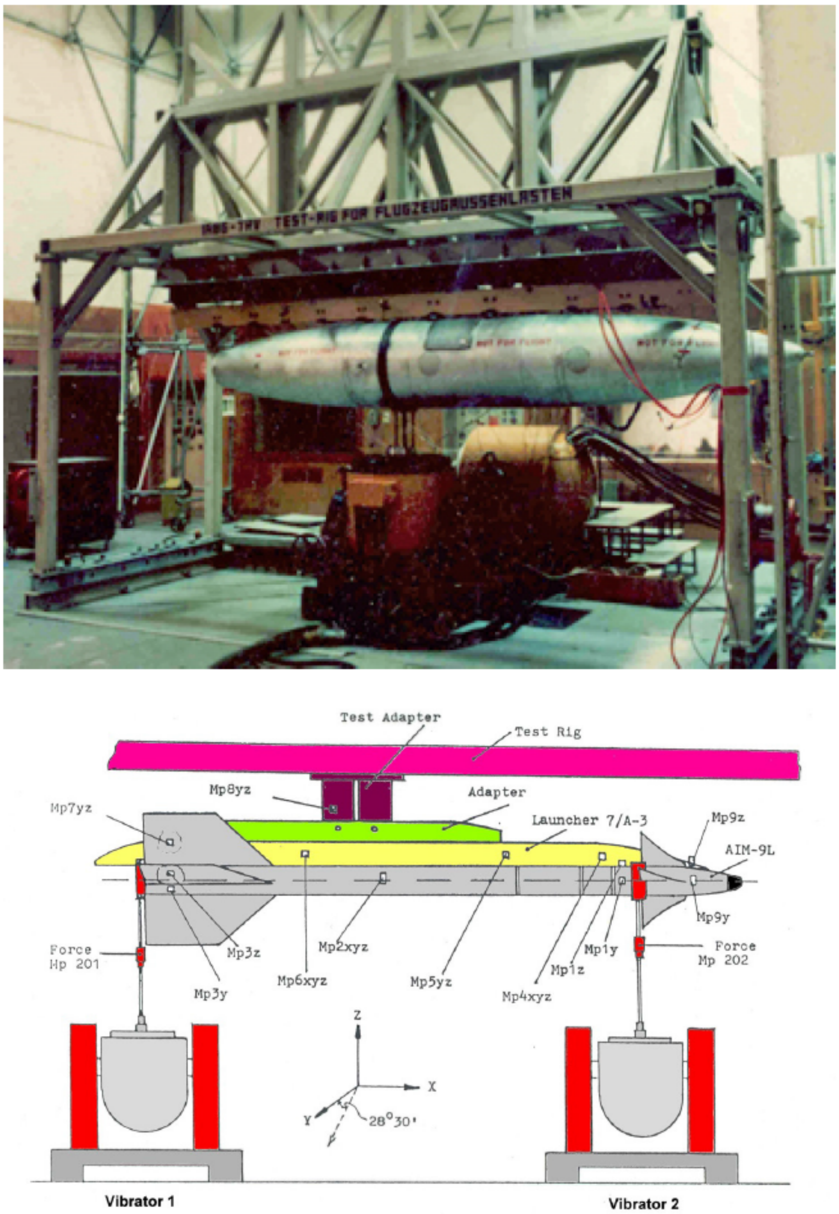

Figure 14: Store Vibration Test Rig.

3.5 Wind Tunnel Test

Wind tunnel testing was often used in the early development phase of a project, but also for the introduction of new configurations. The main purpose for wind tunnel testing is to obtain aerodynamic data, particularly in the transonic regime in the support to flutter and CFD calculations. The data will be used to update both the unsteady and the steady aerodynamic. Different models are required to perform these tests, for dynamic test a dynamic similar model have to be manufactured. Due to the fact that the models are represents the early state of the project, an updating of the models through the improvements during the development phase is very expensive. Beside this there are various areas of uncertainty when performing such tests, for instance: the constraint effects on the tunnel walls and boundary layer, interference effects of the model support and scaling issues resulting from testing at Reynolds numbers much less than those achieved in real flight. For aeroelastic models it is complicated to introduce structural non linearities as a variable and during the test sessions. CFD calculations can be used to provide corrections for the wind tunnel test effects.

Wind tunnel testing is very expensive, both in the construction of scaled models and the use of transonic wind tunnels. Effort is required to make this test more efficient through the use of non-contact measurement approaches and cheaper models.

Figure 15 shows an aerodynamic wind tunnel with external stores. This model was used to measure the aerodynamic polar and therefore the steady aerodynamic derivations of the current configuration. These derivations were used for improving the steady and unsteady aerodynamic. This is important, because the more realistic aerodynamic model can be used, the more accuracy of the flutter, or rapid rolling clearances can be predicted. Figure 16 shows the aeroelastic similar model with external stores. To test a flutter model, special equipment must be available on the wind tunnel. A very quick shoot down equipment must be installed, because the model will be tested up to the flutter onset. In real flutter testing the procedure is a subcritical flutter test. The flutter test will be terminated when the damping levels is less than 3% structural damping.

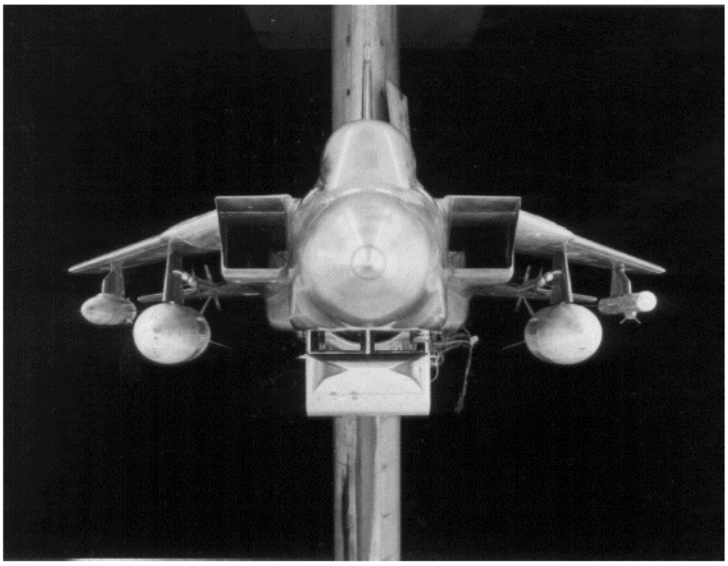

Figure 15: Aerodynamic Wind Tunnel Model with stores.

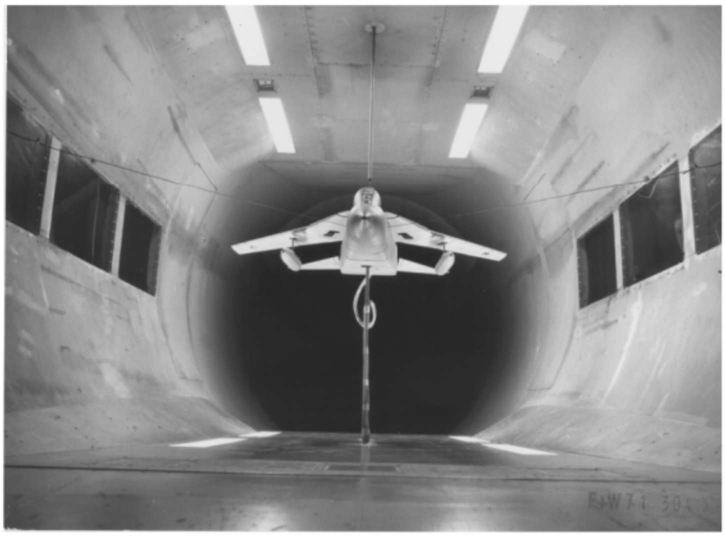

Figure 16: Aeroelastic Wind tunnel Model with external Stores underwing.

3.6 Aircraft Design and its Effect on Flight Flutter Testing

Airframe structures of modern aircraft are nowadays more flexible with less structural damping. The use of high sophisticated structural optimization tools to optimize the aircraft structure with minimum mass has changed the design of the airframe fundamentally compared to earlier designs. The application of modern construction techniques and materials, like composite and super plastic formed – diffusion bonded methods, results in thinner wings and more flexible A/C`s. Besides this, the aeroelastic community are experienced to understand the aeroelastic phenomena's and has validated tools available to predict very precise the aeroelastic behaviour of elastic structures in flight. Recent world-wide research programmes are investigating the use of aeroelastic behaviour as a positive benefit instead of the required stiff and heavy structure. This is only possible with digital flight control systems. Besides this, the essential changes in aircraft design and manufacture have increased the importance on non-linear aeroelastic phenomena, like free play or backlash, stiffening effects, large displacement effects, transonic effects and flight control mechanisms (time delays, non-linear control laws). Limit cycle oscillation is one of the non-linear phenomena which must be investigated in more detail on new aircraft design or change of configuration. Although LCO is not as catastrophic like flutter it must be investigated during the clearance process. At this time the most aeroelastic modelling and therefore the flutter clearance is based on linear methods. Non-linear methods must be considered more often to predict the flutter or LCO more precise for reducing the flight flutter testing.

3.7 Flight Flutter Test Techniques and Excitation Systems

Flight flutter testing is very expensive, time consuming and often undertaken at a time critical of the aircraft development phase. For the first flight of a new aircraft the flutter clearance will be given by analytical work. Applying different specification the aircraft can fly up to the half airspeed of the theoretical flutter boundary. After first flight the structural stability can be shown by measurements during flight. A dedicated programme must be worked out to expand the flight envelope for flutter. If the structure stability is proven by flutter tests, the test A/C can be cleared for other flight tests, like handling and performance. In case of fundamental differences between calculation and test results a model update has to be performed.

As mentioned in the introduction, von Schlippe performed the first flutter test in Germany 1934. The main objective was to reduce the risk for the pilot and aircraft with flutter testing. Before this test the aircraft was flown up to the maximum design speed, to prove the plane is free of flutter.

In principal, von Schlippe's technique consisted the excitation of the structure with rotating unbalance masses in the resonance frequency, measuring the response amplitude and airspeed.

This result was drawn as a function, Figure 17.

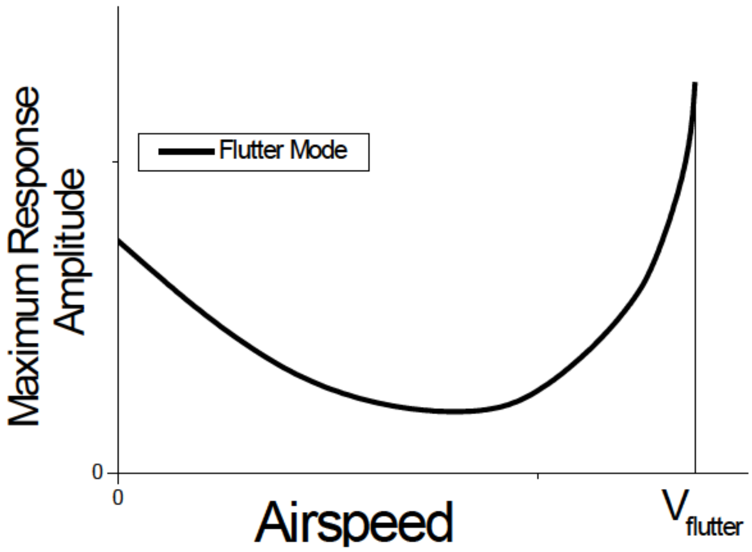

Figure 17: von Schlippe's flight flutter test method.

From 1950 up to 1970, the excitation systems consisted inertia shakers, manual control surface pulses (stick jerks) and bonkers. The instrumentation had improved and a couple of signals were being telemetered to the ground display station as well as written onboard on tape. The telemetry allowed the flutter analyst to follow the flutter flight test on ground. Many aircraft's were equipped with periodical excitation systems. Frequency sweeps were made to identify the structural resonances.

Since 1970's digital computer have significantly affected flight flutter testing technique. The fast computer have allowed to apply the fast Fourier transformation (FFT) and with the parameter identification methods the frequency and damping of a test point could be determined in a couple of seconds after the test point have been performed. These results can be compared with the analytical prediction and if the amount of damping and the trend of the measured slopes are similar to the flutter calculation, the next test point could be performed.

Since the first flight flutter test method has been created by von Schlippe, the techniques have been advanced, but today's techniques are still based on the same three components as von Schlippe's method: Structural excitation, response measurements and data analysis for stability.

For a fighter type aircraft, the required flutter test points are shown in Figure 18. To minimize the risk the test starts with high altitude and low dynamic pressure. For normal testing, the next test points will be chosen on the same dynamic pressure slop up to low altitude. The results will be plotted versus Mach number and airspeed. These allow the flutter engineer to find out Mach number or speed dependencies.

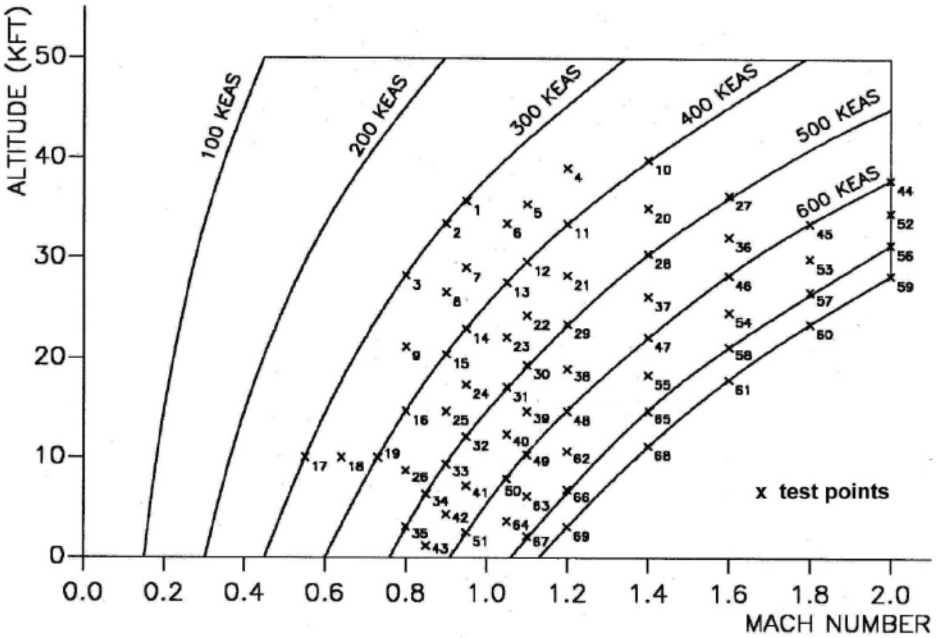

Figure 18: Typical Flight Flutter Clearance Envelope for Supersonic Aircraft.

Table 1 summarises the advantages and disadvantages of the excitation systems used in flight flutter test programme. With introduction of the fly by wire digital flight control systems, the system can be used to inject all different excitation impulses. Before the system can be used the stability of the flight control system must be proven to avoid computer induced oscillations.

Table 1: Flutter excitation system.

Excitation	Signal	Advantage	Disadvantage
Atmospheric Turbulence	Random	No device to be installed	Level of excitation not predictable Excitation not measurable Symmetric and antisymmetric modes are simultaneously excited
Artificial Turbulence	Random	No device to be installed	Excitation not measurable Only usable in restricted A/C
Stick Jerks	Pulse	No device to be installed	Reduced excitation level for higher frequencies (only one mode excited)
Bonkers	Pulse	Simple Installation	Additional masses, restricted number of pulses per flight, location of excitation level for higher frequencies (only one mode excited), problems with scatter and accuracy

Excitation	Signal	Advantage	Disadvantage
Inertia Loads	Free	Effective when in resonance	Additional masses, heavy mass or high acceleration location of excitation not variable reduced excitation level for lower frequencies
Rotary Panel	Periodical	Effective when in resonance	Additional masses, location of excitation not variable, excitation level not selectable in flight, disturbance of aerodynamic flow efficiency depending on A/C speed
Tip Vanes	Free	Effective when in resonance	Additional masses, location of excitation not variable efficiency depending on A/C speed
Control Surfaces	Free	Effective when in resonance, No additional exciter be installed (for flight by wire A/C even no signal generator)	Sometimes reduced excitation level for higher frequencies due to actuator transfer function, interference with A/C manoeuvrability efficiency depending on A/C speed

Figure 19 show the excitation on a flight flutter test at high subsonic speed with low altitude. On this example the excitation was a logarithmic 20 second, generated by a Frequency Response Input Generator (FRIG) Box. This is shown on the very left column of the Diagram. A large response can be seen on the wing tip, with the excitation of the wing bending mode at low frequency. Also large Amplitudes are shown on the inboard store tail in horizontal direction. With this charts the structural damping can be analysed, which is required to further safe testing.

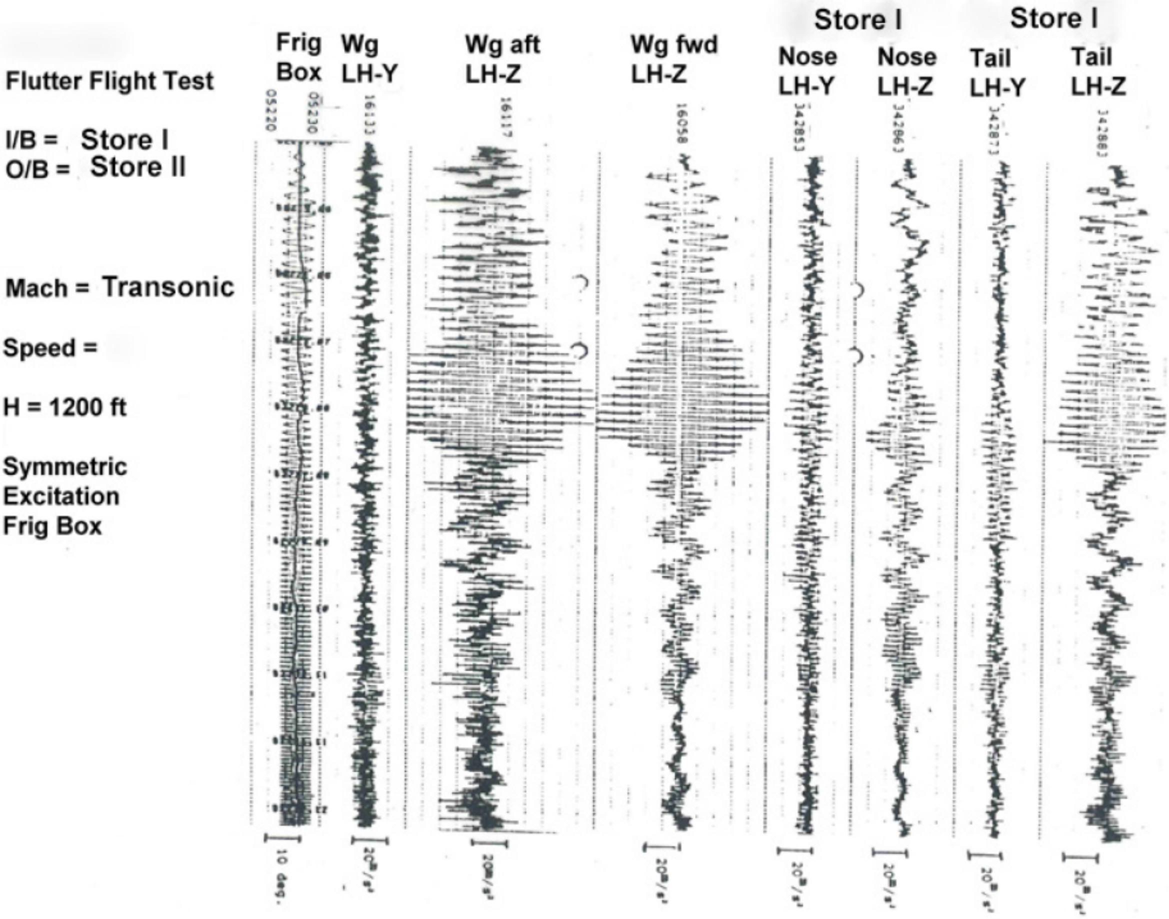

Figure 19: Flight Flutter Test Response on wing and store due to FRIG Box Excitation.

Figure 20 shows the Frequency and Damping survey of a flutter flight test. Four modes were excited. The full coloured lines in the damping diagram show some trends for the flutter prediction on Mode 1 and Mode 2. In some cases it is very difficult to predict the next flutter point due to the large scatter of damping measurements. Sophisticated methods are required to predict the next test point.

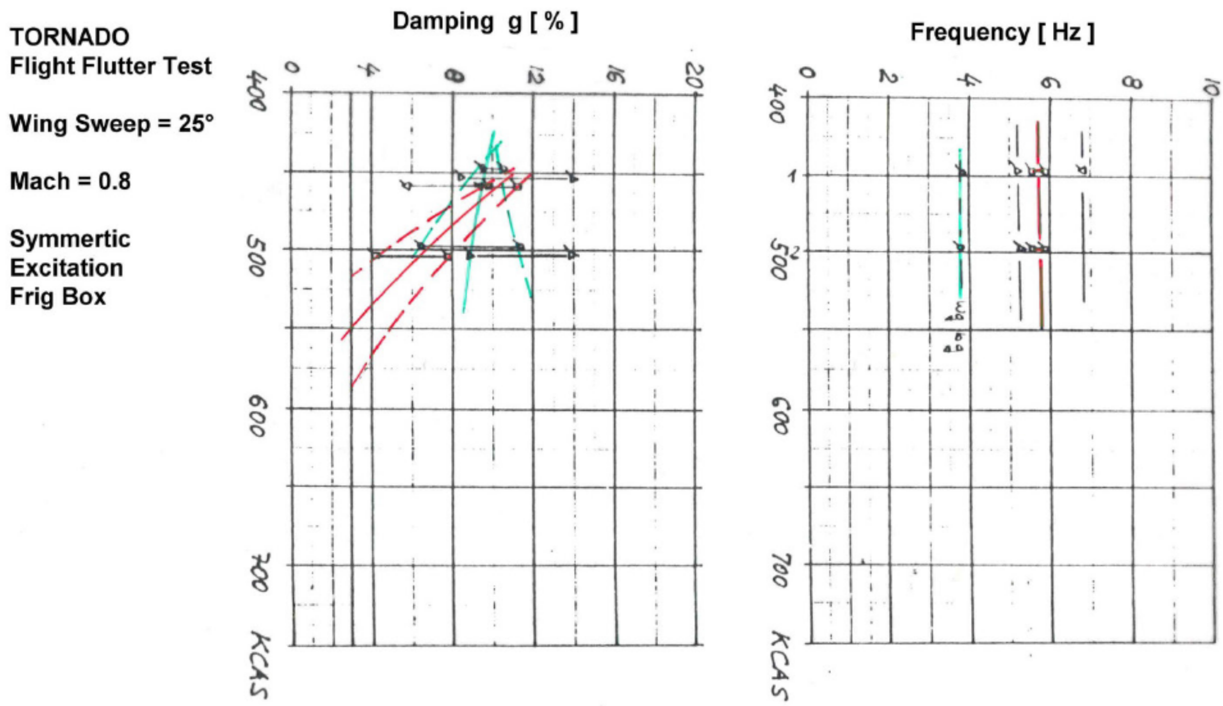

Figure 20: Frequency and Damping Survey, Results of Flight Flutter Testing.

3.8 Analytical Developments for Flight Flutter Testing

The research programmes of the last decade was mainly focused on the modelling and prediction of non-linear aeroelastic effects due to structural, aerodynamic and flight control non-linearity's. Many programmes have tried to identify aeroelastic boundaries by applying coupled computer fluid dynamics and structures codes. There has been much interest in improving the analysis of flight test data in order to determine flutter onset. A lot of non-linearity methods are now available but not yet standard in aerospace industry.

Reductions in time and cost of flutter clearance will be achieved by decreasing the number of required flight flutter tests. To achieve this goal not only methods to predict the flutter boundaries accurate and to evaluate the flight flutter test data more precise can be applied, also the ground test methods and the investigation of non-linearities must be improved.

The term "qualification by analysis" should not include to do every clearance work just with theoretical models, is should focus on methods which consider the complete clearance procedure in terms of reducing test by better prediction. Qualification by analysis should try to clear the aircraft with analytical methods supported by tests.

3.9 Modal Parameter Identification Methods

Different modal parameter identification methods have been applied for flight flutter testing in order to identify natural frequencies and damping ratios. These techniques have been varied in form of a simple half power point analysis to multiple input - multiple output maximum likelihood algorithms. All these methods have been used with the assumption that the system is at a constant flight condition and is linear. Use of mode shapes which can benefit the mode tracking is not common in industrial applied procedures. Large problems arise in measuring the test signals due to the noise of flight in turbulence air. Methods should be available to perform in-flight non-linear identification of the structure.

If it is 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 flutters will not occur, then an exciter could be used continuously to excite the aircraft as the flight envelope is expanded.

3.10 Flutter Prediction Based on Flutter Test Data

The most critical decision during any flight flutter test programme is the decision to perform the next flight flutter test point. This can be achieved by tracking and extrapolating the damping and frequency values and determining whether stability is maintained. If there is a powerful on-line method available a reduction of the test flights is possible. After each test flight the complete determination of the measured damping and frequency values must be performed to compare with the aeroelastic predictions. Methods such as the flutter margin and the envelope function can be employed to use the estimated frequency and damping to predict the real flutter speed are required. A notable development is the use of the μ robustness methodology to predict the flutter speed along with methods based on neural networks and time domain methods. These methods can be used in combination with on-line identification methods to produce safe estimations of the critical flutter speed. Most of the above mentioned procedures work very well only in the linear system. Methods which can track non-linearities like LCO should developed.

4.0 CONCLUSION

This paper describes briefly the elements in aeroelastic / aeroservoelastic modelling and flight flutter testing in the view of determining how flutter flight testing can be performed in reduced time and cost on the same level of risk. Modelling capabilities should be improved to include forms of non-linearity. To make efficient use of CFD based simulations improvements in reduced modelling is required.

It is absolutely necessary to have a reliable dynamic model of the elastic aircraft which must be verified by ground vibration tests.

Ground tests to check structural mode coupling interaction must be performed to assure stability and to compare -, with analytical predictions if correlation is achieved, the variation of parameters such as external stores, fuel content can be investigated analytically Open and closed loop flutter calculations have to be done to cover the full flight envelope.

Flutter test procedures and evaluation of the test results should be extended to allow on-line updating of the structural stability. Non-linear identification methods must be available to predict non-linear phenomenon like LCO from flight test data.

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