EUREKA

FliTE2

PROJECT NAME :	**FLITE 2** **Flight Test Easy 2**
PROJECT NUMBER :	**E ! 3341**
PARTNERS :	**Sopemea, Airbus-France, ONERA, Dassault-Aviation, INRIA, LMS, KUL, VUB, Lambert Aircraft Engineering, AGH, ILOT, (PZL), (Univ. Manchester)**
DURATION :	**48 months (01-Apr 2005 – 01-Apr – 2009)**
BUDGET :	**3.6 (MEuro)**

Flite2 Final Report: Executive Summary

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1. Introduction, Objectives, and Organization of the Project

1.1 BRIEF HISTORY

In 1995, Hermann van der Auweraer (LMS), Michèle Basseville, and Albert Benveniste (INRIA) met and decided to launch a project on In-Operation Modal Identification. They applied to Eureka and got excellent support from this funding program. A series of three Eureka projects resulted, as summarized in the following table.

1996 1999	2001 2004	2005 2008
SINOPSYS	FliTE	FliTE2
Model Based Structural Monitoring Using In-Operation System Identification	Flight Test Easy Shifting focus to aeronautics	Flight Test Easy 2 Pushing FliTE up to transfer
LMS, ISMC, KUL Sopemea, ECP, INRIA AGH, PZL-Swidnik Saab-Aviation (by end of project)	Sopemea, Airbus-France, Dassault-Aviation, INRIA LMS, KUL, VUB AGH, PZL-Mielec, ILOT	Sopemea, Airbus-France, ONERA, Dassault-Aviation, INRIA LMS, KUL, VUB, Lambert Aircraft Engineering AGH, ILOT , (PZL) (Univ. Manchester)
	Budget : 2.7 M €	Budget : 3.6 M€

1.2 FLITE2 REQUIREMENTS

Requirements from aircraft manufacturers can be briefly summarized as follows:

To improve the quality of flight test data analyses;

To enlarge the range of usable flight test data:

For Airbus, current use of flight test data for structure analysis is restricted to stationary operational conditions, in which no change of flight condition occurs, aircraft is subject to no turbulence, and excitation is controlled and caused by control surfaces; aim of FliTE2 is to be able to process data *between* stationary phases, that is, to be able to process data during accelerated flight phases, where dynamics changes;

For Dassault-Aviation, both stationary and nonstationary phases are within the scope of FliTE2;

➔ To allow for exploiting a much wider range of conditions for flight tests. This will be achieved thanks to the use of both input-output and output-only modal analysis techniques;

To offer fully automatic MIMO data processing algorithms

State of the art is that MIMO structural identification requires significant human processing, e.g., through the use of stabilization diagrams and associated GUIs. This does not comply with the conditions in which flight tests are performed. Automatic algorithms and procedures are mandatory.

To improve the reactivity of on-line flight test data analysis:

To develop on-line, in-flight test data processing algorithms; to provide a good quality modal analysis with an update at a rate of 1 sec.

To perform advances on early flutter detection,

To develop additional robust indicators for early warning of possible flutter.

To achieve transfer of new technologies to:

- Aircraft Manufacturers,
- Services & Software Suppliers;

To have impact on flight test teams and software tools.

To have byproducts for GVT and environmental tests, with the objective of reducing testing time and improving quality of results;

These addition al results turn out to be central for the service and software providers involved in the project.

Some targets of FliTE2 are shown in the following pictures: Dassault-Aviation Falcon 2000, PZL Skytruck, LAE Mission M 212, and Airbus A-340. Other aircraft, not shown here, were also considered.

1.3 ORGANIZATION OF THE PROJECT

To better enable transfer, the work was organized into the following Working Groups:

- Trampoline, headed by ONERA and Airbus
- Dassault-Aviation

- LMS-SOPEMEA-LAE
- ILOT-AGH-PZL
- Research on aero elasticity & flutter, headed by INRIA

In addition to the Working Group leader, each Working Group involved (a subset of the) academic partners. The involvement of partners is indicated for each Working Group.

Regarding the development of prototype software during the project, the following process was followed:

- Specifications were formulated by Working Group leaders;
- Prototype software was developed by academic & service partners and was subsequently tested by Working Group leaders or their privileged partner;
- Ultimately, aircraft manufacturers were considered responsible for developing their in-house software;
- General purpose software modules, not specific to aircraft manufacturing, but still resulting from FliTE2 developments, were developed and marketed by software providers.

1.4 ATTENDANCE TO THE CLOSING MEETING

The active participants to the project are highlighted in red.

- **INRIA :** Albert Benveniste, Maurice Goursat, Laurent Mevel; surname.name@inria.fr
- **ONERA** : Pierre Vacher, Alain Bucharles, Patrick Fabiani, surname.name@onera.fr ,
- **KUL**: Jeroen Boets, surname.name@esat.kuleuven.be
- **VUB :** Patrick Guillaume, Tim de Troyer, surname.name@vub.ac.be
- **AGH :** Tadeusz Uhl, tuhl@agh.edu.pl, Andrzej Klepka
- **Sopemea :** Bernard Colomies, name@sopemea.fr
- **LMS :** Bart Peeters, surname.name@lms.be
- **Airbus-France :** Anne Pin-Belloc, Stéphane Leroy
- **Dassault Aviation :** Claire Souty, Laurent Schmitt, Jean-Luc Guillen, Eric Garrigues, Yves Auffray surname.name@dassault-aviation.fr
- **Ilot :** Antony Niepokulczycki, antekn@ilot.edu.pl
- DGA (french administration) : Jean-Marc Espinasse, Nicolas Peteilh
- Eureka : Patrick Palus

2. Achievements and Overall Assessment of the Project

2.1 ACHIEVEMENTS REGARDING FLIGHT TESTS

- New approaches for flutter monitoring during accelerated flight phases have been developed. Observe that no such procedure exists at the moment to process these phases. Having such a service as part of flight test procedures would be highly valuable to aircraft manufacturers in reducing costs while improving safety of flight opening campaigns. One important step achieved by technology providers was to comply with the operational requirements (MIMO, automatic, and on-line procedures while meeting updating rates).
- Dassault-Aviation has developed new software dedicated to both on-ground and in-flight modal analysis, by building on the algorithmic studies performed within the project. This software is now fully integrated in the software suite in use by flight test teams. Also, these new software modules can communicate with other software in use at Dassault-Aviation regarding mechanical design of aircrafts.

- For Airbus, robustness and accuracy of results regarding on-line processing are still not to the level needed to allow for industrial fielding; technical difficulties relate to the presence of fake modes and lack of some real modes. Therefore, full integration of those techniques in the flight test procedures is not completed yet.
- Airbus has improved the methods in use of off-line processing of flight test data by using operational modal analysis through the software developed by LMS in the course of the project.
- Hardware, real-time implementations of automatic, on-line flight data processing have been developed within the project that have been tested and used on-board on PZL aircraft.

2.2 ACHIEVEMENTS REGARDING GVT

- For GVT, current practice relies on phase resonance method (mode appropriation). During FliTE2, phase separation method was improved at SOPEMEA by using Polymax method from LMS and is now in use for GVT.
- LMS worked on the integration of all these methods in the same software platform; this makes phase resonance or normal mode testing, random and MIMO sine sweep testing available for use in GVT. This is important from customer point of view by allowing the user to combine these different methods – different modes are best found by different methods.
- As a result, the same environment is used both for testing and modal analysis. This makes the results of the test immediately available after testing. This is seen as a significant competitive advantage.
- Output-only methods have been used with customers by SOPEMEA for the first time. For some testing configurations, inputs are not available and therefore output only methods are the only way to exploit tests in performing modal analysis.
- The results for GVT are not isolated. They are part of an overall flow that also involves finite elements tools and general simulation environment. (This fact was already mentioned by Dassault-Aviation regarding flight tests.)

Overall, the results for GVT are considered important, although they were not the main focus of the project.

2.3 ACHIEVEMENTS REGARDING RESEARCH ON ALGORITHMS AND METHODS

- The first thing to notice is that research and advances on algorithms has critically benefited from the FliTE/FliTE2 context in may ways:
  - Industrial context ensured relevance
  - Challenging requirements were formulated
  - Realistic simulation models were used to assess the methods
  - Real data were provided
  - Assessment of the algorithms was performed by their candidate users, from industry.
- The series of FliTE/FliTE2 projects has contributed building a best in class community of academics around the topics of the project. Cooperation has been extremely fruitful and satisfactory, regarding both methods and algorithms, and prototype software development.
- The methods developed in the FliTE2 context are indeed quite general, modulo little adaptation. Thus FliTE2 has in this way contributed to the general

area of health monitoring, with byproducts for other sectors than aeronautics, e.g., civil and machine engineering.

- Regarding the algorithms themselves, advances have been made in the following directions:
  - Automatic processing
  - Real-time processing
  - Handling nonstationary data
  - MIMO
- Regarding performance and accuracy of the algorithms, the following can be concluded:
  - There are inherent limits in what data can bring in identifying models; the Cramer-Rao bounds cannot get around and at some point this may call for revisiting requirements regarding the algorithms to be developed. Experimental conditions can only help circumventing this difficulty. In our experiments, we feel we have often been confronted to this difficulty.
  - Not surprinsingly, damping is *the* modal characteristic that is most difficult estimating – unfortunately, it also is *the* critical information needed in flight test data processing.
  - Most methods developed and actually used assume a linear behaviour for the structure; this again is only an approximation, particularly when aeroelastic phenomena become important, e.g., in flutter. However, in FliTE2, several specific techniques to predict or detect flutter have made explicit use of phenomena arising from aeroelasticity (e.g., additional forces that are speed dependent). At this point, it appears that pure "black-box" linear methods perform better than more sophisticated ones regarding on-line flutter onset warning – conclusions may be different regarding flutter *prediction,* where nonlinear effect should not be neglected.
  - Nonstationary effects were another source of difficulty. Flight conditions make the system inherently nonstationary, the worst being when speed conditions change, e.g., acceleration. In case on strong nonstationarity, damping estimates can get significantly affected. The only approach considered in FliTE2 regarding nonstationary effects has been to properly tune "stationary" algorithms to account for time-variations. This can be, e.g., by having explicit parameterization of time variations, or alternatively by handling sliding windows of data of proper size and having truly recursive algorithms involving forgetting factors, or by preprocessing data using wavelet transforms. Again, the obvious conclusion is that there are limits in what you can do with nonstationary effects.
  - Overall, there is no "always better" algorithm. Thus we fell it important to offer different families of methods (subspace, ML, in time and frequency domain).
- Confidence bounds were an important topic for the project. Two types of approach have been considered:
  - Purely empirical approaches, in which confidence bounds were bootstrapped from having a large population of estimates for the same quantity

- Specific estimates exist for most methods and are found in the literature; such methods work reasonably well only for models of moderate size.
    - Confidence bounds were implicitly used in all methods addressing the objective of on-line flutter monitoring.
- Flutter has been a specific topic for FliTE2. It consists in providing one or several of the following services: flutter prediction and flutter margin estimation (sometimes called flutterometer), flutter onset warning, and flutter detection. Several approaches to flutter monitoring were developed in FliTE2:
    - Special tuning of modal identification methods with smaller model order and improved real-time capability (to get shorter reaction time); hardware implementations complement these aspects and make the approach effective.
    - Flutter prediction methods have been developed based on simple aeroelastic models allowing to extrapolate the variations of damping and stiffness and predict the speed at which flutter may occur.
    - Flutter detection methods were developed that do not rely on identification as such but rather use statistical on-line testing techniques. A mix of model based and black-box approaches were developed and experimented and the black-box methods seem more robust.

  Overall, this task has been easier than achieving real-time full size modal analysis with the FliTE2 requirements. Flutter monitoring has proved easier than in-flight modal identification, from the accuracy viewpoint. On the other hand, these methods cannot be seen as mature enough in that they do not fit immediately the current practice of flight test teams. Such teams have little experience in using on-line detection methods as part of their everyday practice. In addition, validation on realistic flutter scenarios is a difficulty by itself, which makes actual fielding more difficult. Additional validation work needs to be done in this direction.

  One nice fact about this topic is that an extremely tight and effective cooperation between all partners has occurred, which certainly played a role in the quality of the results obtained. It is fair to say that some methods, which required background from different partners for their development, would not have been existed without this collaboration.

2.4 COMMENTS REGARDING THE ROLES OF THE DIFFERENT PARTNERS

Roles of the different partners can be summarized as follows:

- Aircraft manufacturers defined the requirements, provided the scenarios for assessing the algorithms, evaluated the results, and took final decision regarding the different methods.
- Software and service providers covered the entire spectrum of project activities, with the exception of providing scenario and data regarding flight tests.
- Academic partners studied the requirements, developed new algorithms, adapted algorithms to the requirements, experimented on scenarios and data provided by the other partners, and transferred their software to the other partners for testing.
- ONERA played a specific role in the project by acting as a privileged partner of Airbus. This means writing and documenting the system and software requirements, preparing an evaluation environment with scenarios of various

difficulties, collecting and assessing the results, and selecting a preferred method for further investigation.

3. Exploitation and Perspectives

3.1 EXPLOITATION

3.1.1 AIRCRAFT MANUFACTURERS

- Airbus: Need to further progress on algorithms regarding robustness; this will be performed by relying on the ongoing cooperation with ONERA. The existing MEFAS tool will be enhanced with some MIMO algorithms. Of course, this new phase will benefit from the results of the project and the increase in background regarding algorithms, at ONERA and Airbus. The introduction of the MIMO algorithms will allow for reducing the duration of flight test campaigns.
- Dassault-Aviation: the new tool resulting from the project is now deployed in Istres. Next step is to perform extensive on-line and in-operation testing of it to achieve proper tuning and to confront the results to current technology. Improvements will eventually result; in case of success, the new tool may become the in-house reference tool for flight tests. The ultimate goal is to link together finite element tools with in flight test tool in order to support the overall design flow.
- PZL (now UTC Sikorsky) applied algorithms and tools developed within the project for testing structural dynamics of Skytruck aircraft. The technology was assessed on the following two problems: 1/ searching lamp attached to the wing changed the dynamics of the structure; they wanted to test in flight the influence of this attachment on the modes; 2/ to assess the dynamic load on this lamp during the flight. Next plans involve the use of this technology in testing helicopters.
- Lambert Aircraft Engineering: gained, from the project, access to sophisticated GVT technology that SMEs normally would not have access to.

3.1.2 SERVICE AND SOFTWARE PROVIDERS

- SOPEMEA: will offer new services by having new algorithms, particularly under output-only conditions. This will reduce the time spent in GVT by allowing more flexibility in combining the different methods to exercise testing. FliTE2 significantly enlarged the technical background of SOPEMEA regarding modal identification techniques and algorithms.
- LMS: part of the project results will be implemented in commercial software for vibration testing and modal analysis. The target applications are GVT and in-flight, as well as environmental testing. Another exploitation will occur through engineering services by widening the range of algorithms and methods offered for testing. The test campaigns performed on Lambert Aircraft Engineering structures serves now as a reference for LMS to enter this market segment.

3.2 COOPERATIONS BEYOND FLITE2

- Newly ongoing cooperation between LMS and SOPEMEA is a key result of the project. Some of the LMS tools developed in the framework of the project are now in use at SOPEMEA and contribute to enhancing the service capability of the latter.

- A cooperation between LMS and the Airbus flight test team has started. Purpose is off-line post-processing of in-flight test data.
- Airbus and ONERA will continue cooperating beyond end of project; the project results have contributed widening ONERA's background and therefore making this institution even more attractive to Airbus.
- AGH and PZL-Mielic established an agreement on continuing research regarding structural dynamics based on the project results.
- LMS is looking forward to continued cooperation with research teams in the general area of system identification.
- In general, there is a wish that this cooperation involving the academic teams will continue in one way or another.

3.3 NON COMMERCIAL SOFTWARE AND HARDWARE TOOLS THAT MAINLY RESULT FROM FLITE2

- INRIA: the **COSMAD** toolbox for SCILAB integrates new generations of algorithms for modal identification and flutter monitoring, as resulting from the project. COSMAD has been transferred to EADS Space Transportation and ONERA-Chatillon, as well as SNECMA-Vernon and is now in use there.
- AGH: Based on the Wavelet Transform and Recursive Least Square algorithms the **Matlab Flutter Toolbox** has been created. The MATLAB Flutter Toolbox allows to perform on-line estimation of natural frequencies (with confidence bounds) and damping ratios for several modes simultaneously. The software covers output-only, input-output, and MISO techniques.
- VUB and KUL: the Matlab modules that were developed in course of FliTE and FliTE2 were transferred to LMS and part of it constituted the background of new commercial products.
- ONERA received software from the academic partners for evaluation in the context of the TRAMPOLINE Working Group. Evaluation was performed on simulated data. Based on this first evaluation, one algorithm was selected and transferred to Airbus for further evaluation on real flight test data.

4. Results from TRAMPOLINE Working Group, ONERA & Airbus France

The main participants to this WG were Tadeusz Uhl and Andrzej Klepka (AGH), Anne Pin-Belloc and Jean Roubertier (AIRBUS), Laurent Mevel, Maurice Goursat (INRIA), Jeoren Boets (KUL), Pierre Vacher and Alain Bucharles (ONERA) and Patrick Guillaume (VUB).

The work accomplished was organized in several tasks summarized hereafter:

- definition of a flutter surveillance procedure : AIRBUS, ONERA
- definition of software specifications : AIRBUS, ONERA
- development of a testing benchmark : ONERA
- development of identification algorithms : AGH, INRIA, KUL, VUB
- evaluation of the algorithms : AIRBUS, ONERA

4.1 GENERAL FRAMEWORK FOR THE WG

The emphasis of the FliTE 1 project was on the *real-time* identification algorithms that could process data in *operational conditions*, i.e. without artificial excitations. An operational framework had to be devised for these output-only identification methods that, as required by Airbus, does not compromise the current approach of flutter testing which is based on series of stabilized test points. Each series includes sine-sweep tests interspersed with several pulse tests.

The concept of the TRAMPOLINE approach (**TRA**cking **M**odal **P**arameters **O**n**LINE**), was to replace the intermediate pulse tests by a *uniformly accelerated* phase where the evolution of the modal parameters would be monitored continuously. This procedure will lead to a substantial reduction of the duration of the flight tests. It also potentially reduces the risk of an undetected sudden flutter between flight points.

Several flight conditions which specified how the structure is excited were considered for the TRAMPOLINE scenario :

- a *background noise* which permanently affects the measurements
- the *air turbulence* which occurs *sporadically*.
- artificial calibrated excitations with two signals : pulse series and multi-sine.

As illustrated in figure 1, the objective for the identification routines is to track in real-time the aeroelastic modes based on initial values computed from the preliminary sine-sweep tests.

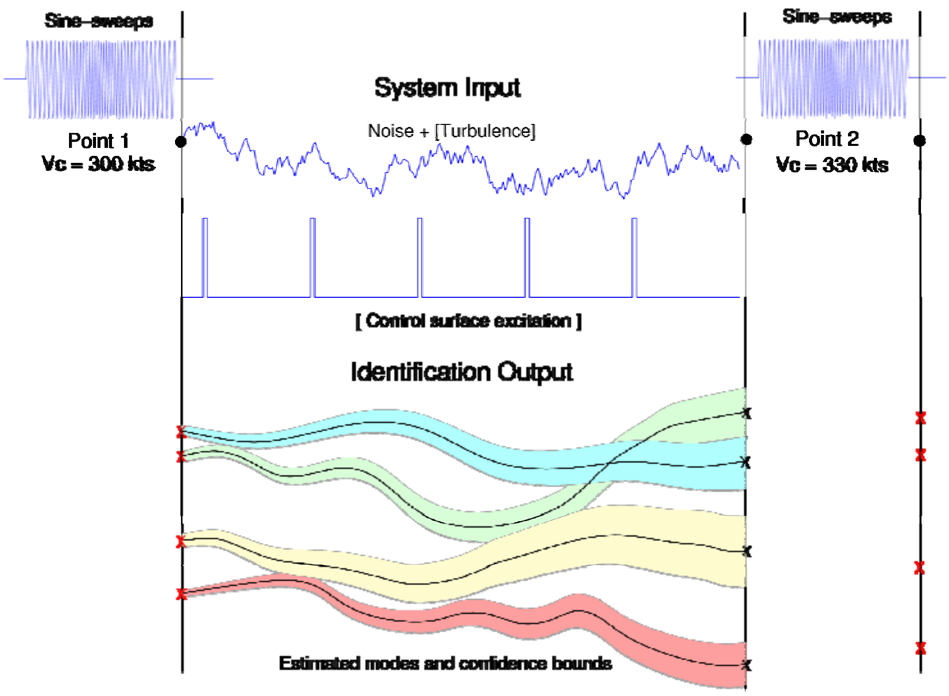


Figure 1: General context for identification algorithms

In order to define unambiguously how the identification algorithms will be integrated and operated in the surveillance system, software specifications were defined. These requirements mainly relies on the standardization of the calling syntaxes of the identification routines.

For several reasons, simulated data were the only way for an accurate assessment of the algorithms on the new testing procedure. A simulation was developed to provide a data basis for the development and the evaluation of the identification methods. The two innovative features of the simulation tool are the efficient integration of a large-scale aeroelastic model on accelerated flight phases and the realistic replication of the in-flight perturbations, i.e. the background noise and the aerologic turbulence.

OVERVIEW OF WG RESULTS

Six algorithms were delivered by the academic partners of the TRAMPOLINE group :

- AGH : Wavelet mode selection and update of the modal parameters by recursive least squares
- INRIA : Covariance driven output-only subspace identification on a sliding window
- INRIA : Input-output subspace identification on a sliding window using projected past inputs and outputs as instruments
- INRIA : Input-output subspace identification on a sliding window by projection on the orthogonal of the input
- KUL : Recursive subspace identification derived from the MOESP method
- VUB : Least-Squares Complex Frequency-domain algorithm (LCSF) on a sliding window

The INRIA and VUB identification procedures are embedded in an automatic mode tracking procedure developed by INRIA which performs the automated extraction of modes from stabilization diagrams and the modes pairing between two consecutive identification operations. The evaluation of the identification algorithms was accomplished in three phases:

- checking their compliance with the functional requirements
- evaluation of the accuracy of the identified modes on simulated data
- evaluation of a selected algorithm on real flight test data

Concerning the first aspect, it was found that all the methods comply with the requirements. On that point, the most notable advances achieved by the academic partners are the development of *fully automatic* and *real-time* procedures.

The evaluation of a selection of four methods on simulated data is summarized in table 1 for several performance criteria. It appears that the method developed by KUL was globally the most performant. It was transmitted to Airbus for a further evaluation on real-flight test data.

Algorithm	nber of tracked modes	track steadiness	modes accuracy	fake modes	flutter detection	real time
AGH	n_{ini}	+	poor	(no)	no	yes
INRIA proj.	1	−	med.	yes	(yes)	no
KUL	3-4	+	med.	yes	delay	yes
VUB	0	−		yes	no	yes

Table 1: Global evaluation results on simulated data

The evaluation on real data was performed on a flight test similar to the TRAMPOLINE scenario. Though the algorithm seems to be able to track a few modes, the method is not robust enough to be implement in Airbus testing center. The main drawbacks are the number of fake modes, the sudden and inappropriate decreases of damping estimates that would lead to improper stops of the test underway, the real-time development of a mode track formation method appropriate to the flutter surveillance.

4.3 CONCLUSIONS AND PERSPECTIVES

In spite of the significant improvements that were accomplished on the identification methods during the project, the overall conclusion of the WG is that none of the algorithms is sufficiently mature to be transfered in the telemetry center of Airbus. The main achievements of the WG were

- the development of a new and attractive procedure for flutter testing
- the associated and realistic simulation of flight test data
- the development of innovative features for identification algorithms: real-time processing, automatic processing, identification of time-variant MIMO systems

Yet improvements are still necessary for the algorithms to be transfered to the industry and to be used operationally. The main points to be improved are the accuracy, the representativeness and the steadiness of the identified modes and the timeliness of flutter onset detection.

The actions performed in TRAMPOLINE also gave rise to challenging future research orientations for the academic community in identification:

- the recursive identification of time-variant systems
- the identification of parametrized systems

5. Results from Dassault-Aviation Working Group

Main participants to this WG were Claire Souty (Dassault-Aviation) and Laurent Mevel (INRIA); Laurent Mevel served as a tight link to Patrick Guillaume and Tim de Troyer (VUB).

5.1 THE ALGORITHM SELECTED AND THEIR INTEGRATION IN THE DASSAULT-AVIATION TOOLSET

Several algorithms developed in the frame of FliTE and FliTE 2 projects have been compared on simulated data in order to select the one that satisfies the specifications as well as possible.

Frequency domain method based on the LSCF (Least Squares Complex Frequency domain) algorithm has been adopted because it has the following advantages: very short computational time, results are stable and accurate, stabilization charts are clear with few mathematical poles, ability to take a lot of sensors into account.

With help from the selected algorithms, a new software for modal analysis has been developed within Dassault aerostructures in-house tools, in relation with existing tools. This software is called ALAMO (ALgorithm for Aircraft MOdal analysis). It is now fully integrated in the design and test process of Dassault Aviation, and can run in relationship with Dassault in-house computing tools.

A series of validations were necessary to check the implementation and the interactions with other computational tools. After that, the performances of the algorithm were evaluated on ground vibration, wind tunnel and flight tests. The results were compared to reference tools in terms of modal analysis: phase resonance method for ground vibration tests and in-house LAMEV software for flight tests.

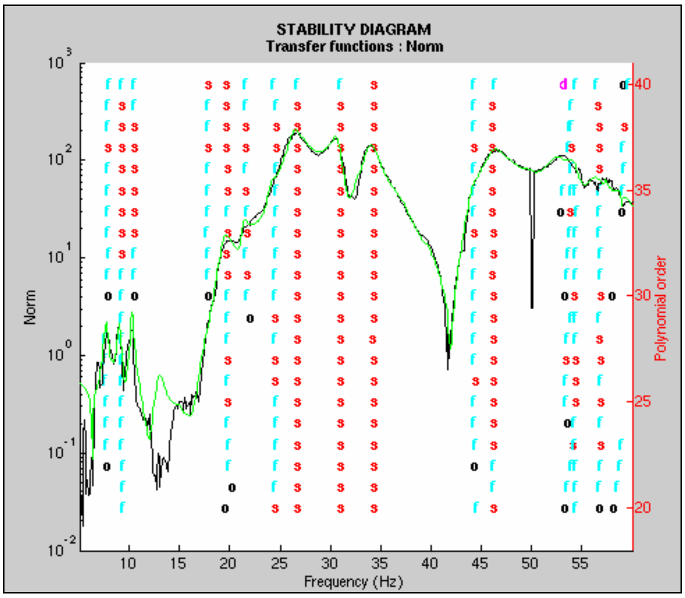
5.2 BRIEF OVERVIEW OF RESULTS

In order to illustrate the performances of the new ALAMO software, the following tests are analyzed in this report: Falcon 7X ground vibration test and Rafale in heavy configuration flight test.

5.2.1 FALCON 7X GROUND VIBRATION TESTS

Ground vibration tests have been performed before the first flight of the Falcon 7X. On one hand the traditional phase resonance method has been performed. The plane was excited with fixed sine waves thanks to shakers, and the response of the structure was measured with 500 sensors approximately. Reference and accurate results have been obtained thanks to this method. One the other hand, phase separation method has been tested. The control surfaces were used to excite the structure with a sweep sine, and the same sensors measured the response of the system. Post-treatment was performed thanks to Dassault new modal analysis algorithm ALAMO.

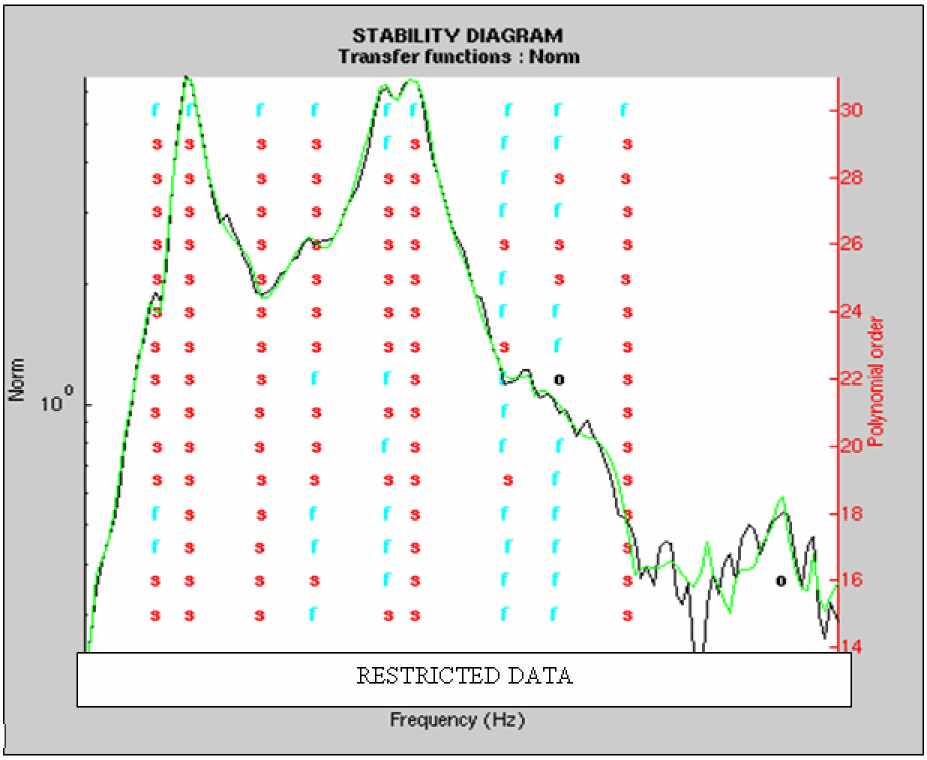
The figure below shows a stabilization chart with the measured and estimated transfer functions of one particular sensor located on the horizontal stabilizer. This figure illustrates the quality of stabilization diagrams obtained by this method. The results obtained with this new method are in accordance with those obtained with the reference phase resonance method but are cheaper to use.

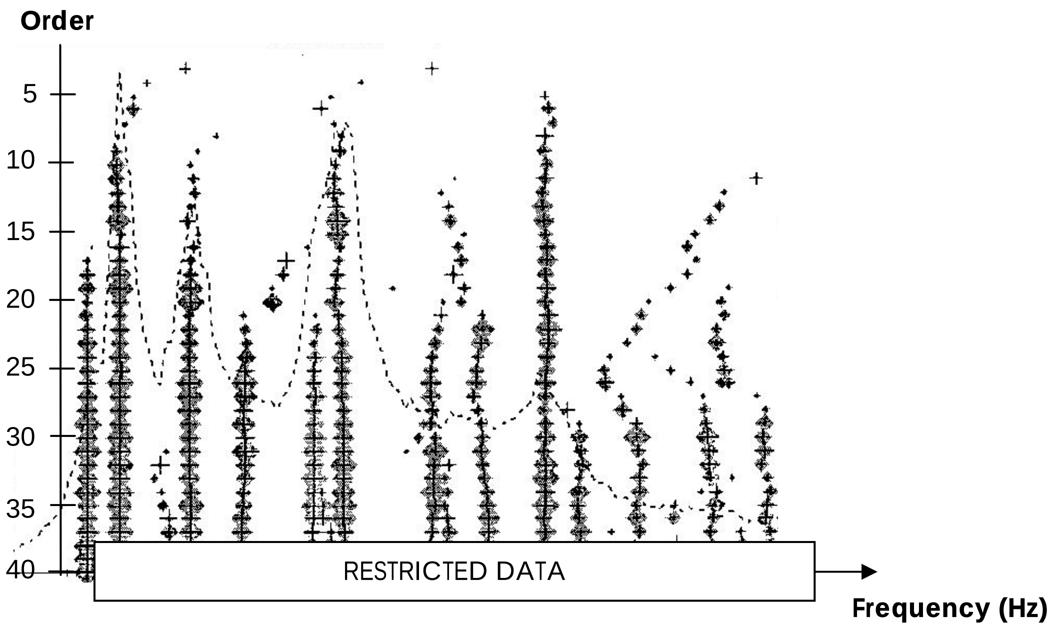


's' : stable pole (frequency and damping)
'f' : stable frequency
'd' : stable damping
'o' : unstable pole

5.2.2 RAFALE IN HEAVY CONFIGURATION FLIGHT TEST

Flight tests have recently been performed on Rafale in heavy configuration. The aircraft was excited with its own control surfaces, and around 20 accelerometers were positioned on the structure to record the vibrations. Dassault Aviation modal analysis method was performed and reference results were obtained. In a second step, the new ALAMO algorithm was run and its results were compared to the reference method LAMEV in use at Dassault-Aviation. The following two figures allow comparing the results obtained with the new ALAMO method and the reference method LAMEV. Results obtained by the ALAMO method are in accordance with those previously obtained with the LAMEV method.





5.2.3 CONCLUSIONS AND PERSPECTIVES

In the frame of the EUREKA FliTE 2 project, Dassault Aviation has developed a new set of tools for modal analysis : ALAMO (ALgorithm for Aircraft MOdal analysis). This new method is currently tested at Dassault flight test centre in Istres in order to be compared to Dassault reference flight tests software.

The advantages of ALAMO are the following :

- Very short computational time (a few seconds),
- Clear stabilization charts with very few mathematical poles,
- No use to select the appropriate sensors to identify each mode (including broken down or disturbed sensors),

- Mode shapes computation to help naming the modes and identifying couplings between modes,
- ALAMO is fully integrated into Dassault design and test process,
- Close relationship between ALAMO and Dassault Aviation in-house design and computing tools.

ALAMO will soon be tested on real flight tests in parallel to the current flight test software. The objective is to check the performance of the new method in real conditions of a flutter clearance flight test. In the future, ALAMO could become the reference tool for flight tests analysis.

In parallel, an online damping tracker algorithm has been developed by INRIA and tested on simulated flight data. This approach demonstrates that it is possible to get information about the evolution of the modal parameters between two stationary stages without performing a "heavy" modal analysis. However, the results still need to be improved to reach the required robustness for an industrial application.

6. Results from ILOT/PZL/AGH Working Group

Main participants to this WG were Tadeusz Uhl and Andrzej Klepka (AGH), and Antony Niepokulczycki (Ilot).

The main goal of this group has been development of in flight structural dynamics with special focus to detect changes in modal parameters due to changes of flight conditions.

Several tests of Skytruck airplane have been conducted within the project frame. The commercial goal of several of these tests was to detect changes of structural dynamics parameters due to modifications of airplane design. The method for in-flight loading forces estimation has been developed by AGH team, but applied for detection of loads of PZL Skytruck during different missions. The identified forces have been used later on for prediction of fatigue and strengths of materials for different airplane components. Particular example of this application has been prediction of dynamic behavior of the structure after its modifications. The second task for the working group was in flight flutter detection technology transfer from AGH to PZL for different applications for their projects. The technology has been demonstrated during real life experiment on an aircraft.

AGH cooperated closely with all project partners in the area of:

- Algorithms development,
- Algorithms testing
- Testing of hardware flutter monitoring solution

Flutter detection algorithms have been developed in cooperation with ILOT. Algorithms testing have been performed with LMS based on their commonly use software and ONERA within TRAMPOLINE working group based on AIRBUS model data. The algorithms and developed software have been employed for Skytruck in-flight test. PZL Mielec helps to deliver real data from in-flight measurements for algorithms testing. ILOT supplied real data from wind channel testing of air jet wing, as well as real data from flutter in-flight test of ISKRA training jet. The hardware solution of flutter monitoring designed and implemented by AGH has been tested during a flight of PZL Skytruck airplane.

7. Results from the Working Group on Ground Vibration Tests, LMS & SOPEMEA

Main participants to this WG were Bart Peeters (LMS International), Bernard Colomies (SOPEMEA), Filip Lambert (Lambert Aircraft Engineering).

Main objective of this Working Group was to develop methods that reconcile reduced testing time with extended measurement specifications. These testing methods deliver more information in a shorter time.

Very specific for aircraft testing is the combined use of different vibration excitation techniques (Figure 1). The following results were achieved in the GVT Working Group.

A critical assessment of the harmonic estimator for sine tracking was made. The influence of the presence of noise, higher harmonics, and other frequency components close to the excitation frequency was investigated. The latter is simulating a sine sweep scenario just after passing through a lowly-damped resonance: it will take very long before this signal decayed sufficiently. It was found that the harmonic estimator is very robust against noise: even with 50% rms noise added very acceptable estimates were found. Higher harmonics do not influence the estimate as long as an integer number of periods is observed. Unfortunately, the presence of a frequency component close to the excitation frequency is a problem (or more general: the non-stationary nature of the sweep excitation and the presence of transient effects which are a consequence of this). The harmonic estimator suffers from the trade-off between selectivity and speed and as a result, for fast sweeps inaccurate estimates are obtained (Figure 2). Therefore alternative methods are investigated to obtain FRFs from sine sweep data.

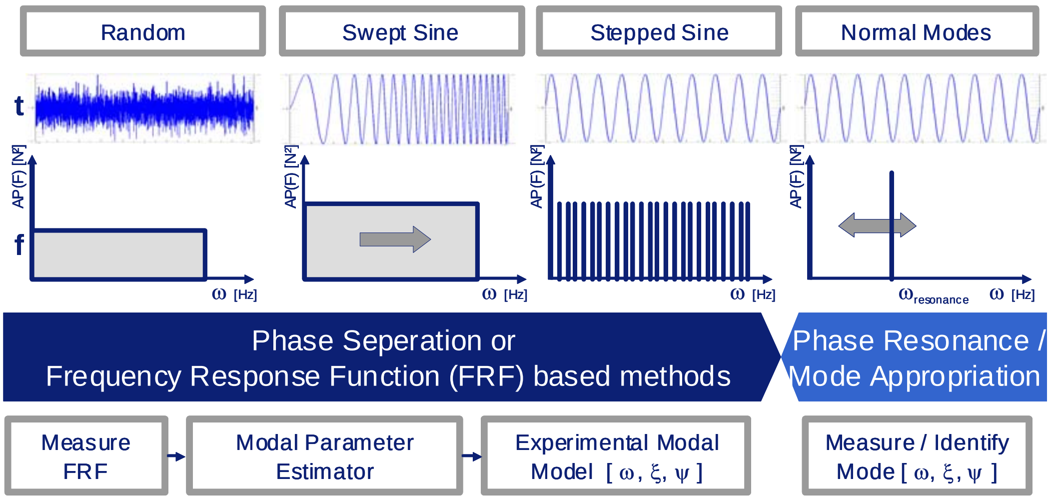


Figure 1: Dynamic excitation signals and modal parameter estimation strategies in Ground Vibration Testing.

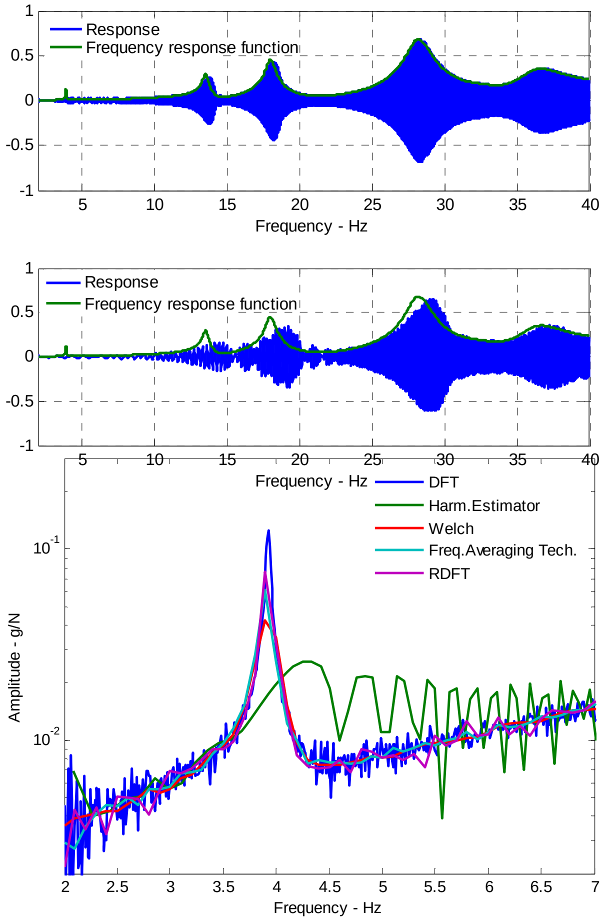


Figure 2: (Left) Effect of the sweep rate (slow = top, fast = bottom) on the responses. (Right) Comparison between the FRF estimators. The instability of the harmonic estimator is evident.

These methods are all DFT-based and operate either in a block-average mode or are applied to the complete time recordings of a sine sweep test. Main advantage of the block-average mode (such as Welch's averaged, modified periodogram method involving the use of e.g. a Hanning window or the unwindowed “reduced” DFT approach) is that spectrum and FRF estimates become available during the measurements and that the typically very long complete time data does not need to be stored nor processed afterwards. The single DFT method complemented with spectral-line averaging has the advantage that a good noise reduction is obtained. The different estimators have been studied, implemented, validated and critically compared using simulated data (Figure 2) as well as real MIMO sine data acquired on the GARTEUR scale model at SOPEMEA and the Mission M212 aircraft at LAE on the LAE Mission M212 aircraft (

Figure 3).

Figure 3: Validation of Advanced Testing methods using the GARTEUR scale model at SOPEMEA (Left) and the Mission M212 aircraft at LAE (Right).

Typical GVT user scenarios were investigated (Figure 4) in order to minimize the overhead and loss of time when switching from one excitation technique to the other. Commonalities between the techniques were defined to prepare the route to an efficient commercial software implementation.

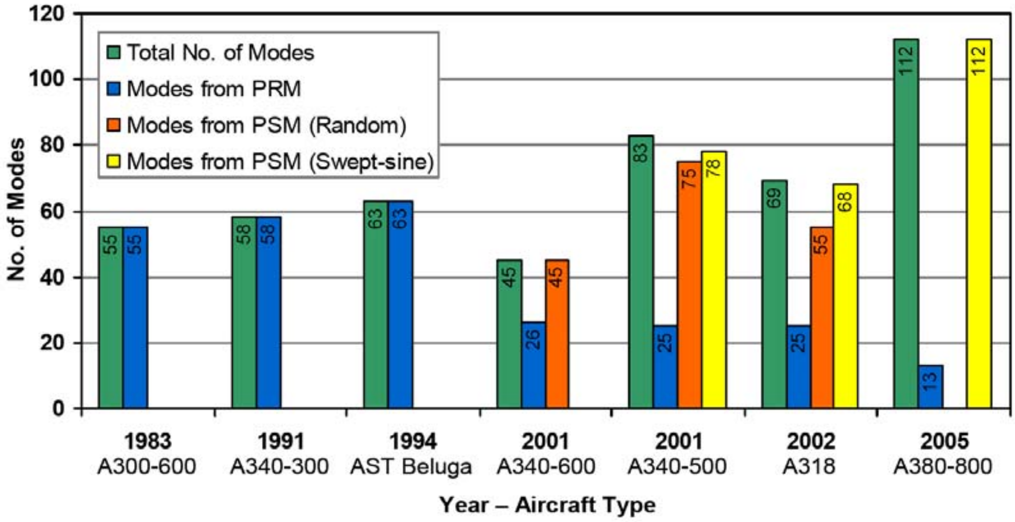


Figure 4: Test strategies for large Airbus aircraft. Source: D. Göge, M. Böswald, U. Füllekrug, P. Lubrina, "Ground Vibration Testing of Large Aircraft – State-of-the-Art and Future Perspectives", In Proceedings of IMAC 2007.

The PolyMAX estimator was modified so that it could also analyse non-equidistant FRF data. Such data is for instance obtained when performing logarithmic sweep testing or when performing a stepped sine test at an irregular spacing of frequency lines. It was for instance found that very good identification results are obtained when only a few spectral lines around the resonances are available (Figure 5): the stabilization diagram was still nice and very accurate pole estimates are obtained.

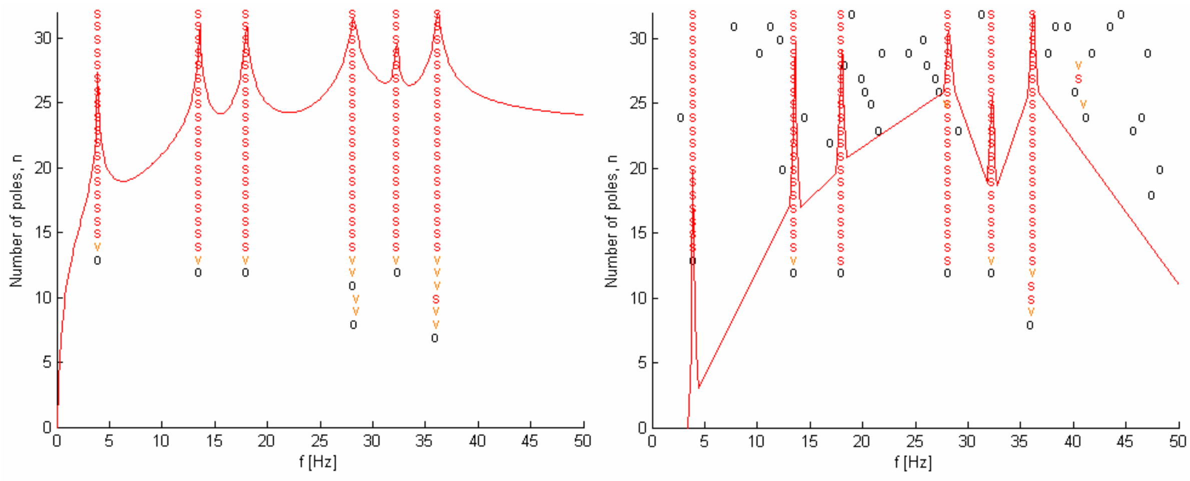


Figure 5: (Left) PolyMAX using all data; (Right) “non-equidistant” PolyMAX using only limited number of spectral lines around the resonances.

The developed GVT methods were validated using the GARTEUR aircraft scale model at partner SOPEMEA and the Mission M212 at partner Lambert Aircraft Engineering (

Figure 3). Since during the research stage, no commercial solution was available, two LMS Scadas and Test.Lab systems were used: one for controlling the test (MIMO sine sweep) and the other for acquiring time histories that could afterwards be processed offline in the algorithm prototype environment.

Part of the validation of the methods developed in FLITE2 could also be performed on large Airbus aircraft. Figure 6 represents some A330 mode shapes identified using PolyMAX applied to MIMO sine sweep data. Figure 7 shows a result from a Normal Modes test, during which also the aircraft non-linearities were investigated. Finally, the GVT results were also embedded in aircraft design process by providing interfaces between the structural dynamics FE Models and the aero-elastic panel models (Figure 8).

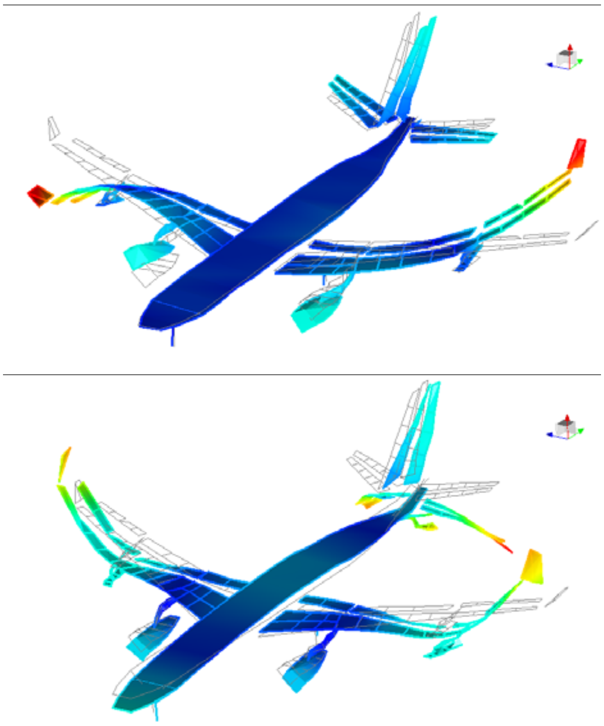


Figure 6. A330 mode shapes.

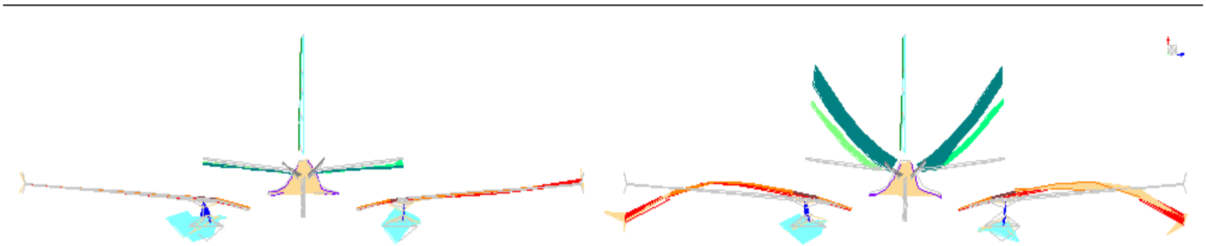


Figure 7: Mode shape visualisation typically used in Normal Modes testing: coincident and quadrature part.

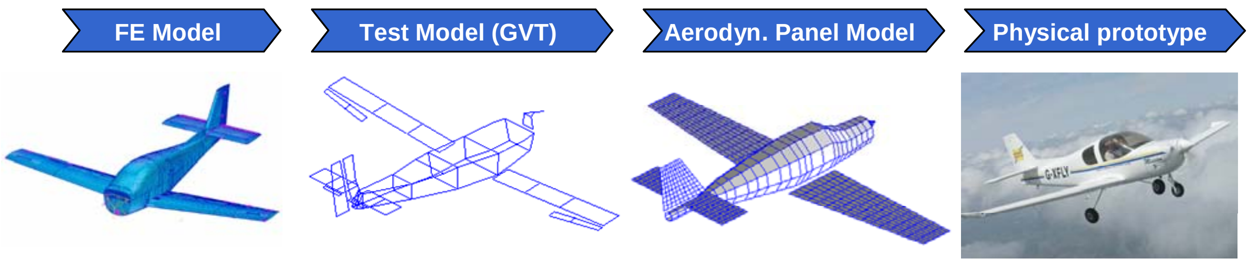


Figure 8: Ground Vibration Testing as a part of the design process of a new aircraft – Illustration using the Lambert Aircraft Engineering Mission M212 aircraft.

8. Results from the Working Group on research regarding Flutter, the academic partners

Main participants were Laurent Mevel (INRIA), Patrick Guillaume and Tim de Troyer (VUB), Jeroen Boets (KUL); Jonathan Cooper (University of Manchester) was co-leading the group with Laurent Mevel before leaving FliTE2 due to lack of financial support by UK.

8.1 STRUCTURAL IDENTIFICATION: IN FLIGHT USAGES AND SCENARIOS

Patrick Guillaume, VUB: time-domain implementation of the least-squares complex frequency-domain estimator for on-line identification of modal parameters

The development of the Least-Squares Complex Frequency-domain (LSCF) estimator is based on the well-known Least-Squares Complex Exponential (LSCE) estimator. However, both estimators are not 100% equivalent. For instance, the LSCF estimator can identify the full modal model while the LSCE estimator can only be used to estimate the global modal parameters (poles and modal participation factors). In this contribution the exact time-domain equivalent of the LSCF estimator has been derived. In application such as flight flutter testing and structural health monitoring on-line identification techniques are a benefit. Unfortunately, frequency-domain estimators are not suited for on-line implementations. By converting the frequency-domain LSCF estimators to a time-domain equivalent estimator, a recursive on-line implementation of the LSCF estimator becomes possible. One important advantage of frequency-domain estimators is the possibility to introduce frequency-dependent weighting functions. These frequency-dependent weighting functions, when properly selected, can result in a significant reduction of bias and variability errors. One concludes that a significant improvement of the "on-line" damping estimates can be obtained by pre-filtering the data with a digital filter that mimics the optimal maximum likelihood frequency-domain weightings.

Patrick Guillaume, VUB: estimating confidence intervals

The least-squares complex frequency-domain (LSCF) estimator — commercially known as the PolyMAX estimator — nowadays is used intensively in various modal analysis applications. The main advantages are the very clear stabilization diagrams and even more important, the speed. In this contribution it is shown that confidence intervals of the modal parameter estimates can be derived without major additional calculations, if the frequency response functions are uncorrelated and noise information (e.g. the coherence function) is available. This approach is also applied to the iterative quadratic maximum likelihood (IQML) estimator, indicating strong analogies to the maximum likelihood (ML) estimator. The algorithm is evaluated by means of Monte Carlo simulations.

One major drawback of the PolyMAX estimator, a polyreference least-squares frequency domain estimator, is the lack of confidence bounds on the estimated modal parameters. This contribution proposes a fast two-step approach to determine the variances on the estimated polynomial parameters and next on the resonance frequencies and damping ratios. The approach is based on the linearization of the sensitivity of the modal parameters to the noise variance. This noise variance (explicitly or as the coherence function) is assumed to be known a priori. The approach is tested on simulations and real-life measurements.

Laurent Mevel, INRIA

INRIA has investigated the tracking of modes during in flight conditions by using two different approaches, namely identification and detection.

First, an automated online implementation of the covariance subspace algorithm has been developed. The main concern was the overall speed of the algorithm given the in-flight requirements. Special attention has been devoted to this problem by a few specialized modules devoted to the selection of best sensors, the automated selection of relevant modes from the subspace stabilization diagram and the implementation of recursive computation for the difference considered algorithms. Confidence intervals were estimated empirically and a graphical plot of the online tracking of modes was provided. For the scenarios provided by Flite2 partners, flutter was detected as the drop of the most important mode.

Second, and in parallel to the development of flutter warning tools by on-line change detection methods, subspace based damping monitoring was investigated and tested on simulations of a two engines aircraft under acceleration with good results. Real-time tracking of some critical damping modes was performed without explicitly identifying those parameters.

Tadeusz Uhl, AGH

A formulated algorithm by AGH team allows estimation of modal parameters of complex airplane structures on-line during a flight. Two scenarios of data processing are possible; on board of aircraft and at ground station using telemetry system. For the first scenario the hardware implementation in a form of flutter monitor can be used. But for second one the Matlab Toolbox is dedicated. Hardware implementation of the flutter monitoring algorithm is proposed with the Hardware-Software Co-design approach, i.e. a part realized by hardware and the remaining part by software running on a Nios II soft-processor contained in the FPGA. The flutter monitor is an example of the System-on-Chip, which allows for high level of integration and flexibility – it can be altered, e.g. to optimize for different algorithms, or to add some functionality, by reprogramming the FPGA without modifications of the PCB. For the tested structure, 12 first modes parameters have been identified simultaneously during 0.001 second. Confidence intervals for all parameters are relatively small and the method can be applied for flight flutter testing based on in-flight measurements. As it was shown the results are very similar to results obtained using different classical methods realized off- line. The flutter monitor has been installed on a board at Skytruck and tested during a flight.

Jeroen Boets, KUL

For the on-line tracking of the modal parameters of a time-varying system two recursive subspace identification algorithms based on the non-recursive MOESP subspace algorithm have been implemented by the KUL team. Two main operations in subspace algorithms are the LQ decomposition and the singular value decomposition (SVD). The first operation can efficiently be implemented in a recursive setting by using Givens rotations. The SVD however is not suited in a recursive implementation due to its computational complexity. Therefore, to circumvent the SVD, both recursive algorithms make use of an adaptive signal processing technique for direction of arrival estimation, namely the propagator method. This results in the replacement of the SVD by the recursive solution of a minimization problem. Both recursive algorithms also include a forgetting factor in order to reduce the influence of previous data compared to new measurements. This is needed in case of tracking a time-varying system. The tuning of this forgetting factor is a critical step to obtain satisfying estimates for the system parameters. Both recursive algorithms were applied to stationary in-flight data. One of the algorithms was selected and its code was adapted to comply with the specifications of AIRBUS-ONERA in the TRAMPOLINE working group. The algorithm was then applied to simulated non-stationary flight data provided by AIRBUS-ONERA, which showed that the algorithm is fast enough for on-line implementation. Another conclusion was that the damping of the mode tending toward flutter was tracked quite closely (however with some delay), thus allowing to detect the onset of flutter in these simulated data. A disadvantage of the method is the appearance of some fake modes and the sensitivity to the choice of the forgetting factor.

8.2 FLUTTER MONITORING : PREDICTION, DETECTION, AND TRACKING (ALL REAL-TIME AND DURING FLIGHT)

Laurent Mevel, INRIA: on-line early warning of flutter

Flutter monitoring was the main concern of the Flite2 funded thesis of Rafik Zouari. Different methods have been developed to address the problem of flutter warning. Those methods monitor if recent data are coherent with some reference model taking into account modal sensitivities and noise information. Those methods are real-time, robust to non-stationarities and perform well on the in-flight scenarios tested during the Flite2 project, namely those corresponding to large aircrafts. The different methods differ by the way they compute the reference model, namely:

- A prediction based approach has been developed in cooperation with VUB to monitor the apparition of flutter in between flight points.
- An adaptive approach has been developed to monitor the drop of the damping, and consequently the increase of its dynamics, a critical behavior arising before flutter.

Those methods would not have been developed without close collaboration with some partners, e.g., the use of wavelet filters of AGH for model reduction in preprocessing.

Tadeusz Uhl, AGH: RLS based algorithms for tracking fast changes

AGH developed three kinds of algorithms:

- RLS based algorithms for real-time structural modes monitoring,
- Wavelets based signal preprocessing to reduce model order
- Automation of stabilization diagram interpretation,

The structural modes tracking algorithm consist with two main parts. First part which is preprocessing part consists in computing the Morlet wavelet transform of measured signal. Based on the time-frequency representation, measured vibrations are decoupled into single modes. Then Recursive Least Square method is applied for model parameters estimation. Advantages of this approach are reduction of the model order. For decoupled system order is known and equal two. This approach reduces time consuming for model (and modal) parameters estimation. The next advantage of proposed algorithm is possibility to estimate of confidence bounds for natural frequency and modal damping ratio on-line with parameters. The algorithm can be applied as Output Only, Input-Output and Multiple Input Single Output. The algorithms dedicated for automation of stabilization diagram proposed by AGH are based on natural networks and fuzzy reasoning.

Patrick Guillaume, VUB: A new frequency-domain flutter speed prediction algorithm using a simplified linear aero-elastic model

This contribution discusses a new flutter speed prediction method. Flutter is a dynamic aero-elastic instability of surfaces exposed to wind, e.g. aircraft wings. Current flight flutter tests trace damping ratios evolution with aircraft speed and then extrapolate these linearly. The critical flutter speed is found when one of the damping ratios becomes zero. The proposed method fits identified modal parameters at different flight speeds to a quasi-steady aero-elastic model. The flutter illustrated in this model results from the dependency of the coupled structural-aero-dynamical damping and stiffness with speed that leads to instability. In this way, the denominator of the transfer function of the dynamic system is a polynomial function of the Laplace variable and the speed. The coefficients of this denominator are identified for different speeds and then extrapolated to other speeds. The damping ratios are predicted in a second step from extrapolation to estimate the critical flutter speed. As this extrapolation method is physically more justified than the classical linear extrapolation of the damping ratios, the prediction of the flutter speed will be more reliable. Moreover, the identification process is ideally suited to the frequency domain, so use can be made of state-of-the-art frequency-domain identification algorithms. The proposed approach has been tested using flutter simulations and compared to classical prediction methods.

9. Additional information available from FliTE2 web site

The following information is available on the public FliTE2 web site (link??)

- Selected papers: 3-5 for each team (pdf put on site); the report will contain the ref and the web site will contain both ref and paper
- Links to personal web pages of key persons together with a 5 lines summary of activity for each person.

9.1 SOME USEFUL LINKS

The url listed below point either to personal pages of key participants to FliTE2 or to relevant pages of the partner's Web sites.

AGH

INRIA

http://www.irisa.fr/sisthem/constructif/modal.htm COSMAD link

http://www.irisa.fr/sisthem/index-en.htm

http://www.irisa.fr/sisthem/lmevel/index.html

http://www.irisa.fr/sisthem/michele/mb-engl.html

http://www.irisa.fr/distribcom/benveniste

KUL/SISTA/SMC

http://homes.esat.kuleuven.be/~smc/

LMS

http://www.lmsintl.com/testlab/structural

http://www.lmsintl.com/download/technical-papers

ONERA

http://www.cert.fr/dcsd/idco/perso/Bucharles/

http://www.cert.fr/dcsd/idco/perso/Vacher/

VUB

http://www.avrg.vub.ac.be/

http://mech.vub.ac.be/avrg/members/patrick.htm

SOPEMEA

http://www.sopemea.fr/

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