항공기 구조물의 동적 거동 시험/해석 절차

An Integrated Approach to the Dynamic Testing of Aerospace Structures

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Key Words : GVT(Ground Vibration test), Phase Resonance test, Phase Separation test, Mode tuning test

ABSTRACT

Ground Vibration Tests (GVT) are needed on all new aircraft types and as part of certification. Its first objective is to verify models used for the calculation and prediction of the dynamic behavior of the structure. The main objectives of this paper are to introduce "the integrated approach of dynamic testing for aerospace structure" in detail and "The research projects in which LMS participated in aerospace structural dynamic area"

1. 서 론

What is critical for the success of a dynamic test of an aircraft, spacecraft or satellite?

– Time. Flight dates are extremely close and the planning of all the tests are extremely tight. Reducing the test from 2 weeks to 2 or 3 days would have an enormous impact.

– Flexibility and reliability. The test team is faced with an increasing amount and variety of verification tests to be performed.

– Integration of modeling and test data. Test and design teams need to work together. Tests must be prepared carefully and making use of all available information such as the Finite Element model; tools must be available to efficiently use this information to prepare the test; every bit of information from the test needs to be exploited to verify or calibrate the models used for the prediction. Tests are not "standalone" activities, they must be streamlined in the total design process, their results must be integrated in the design verification.

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2. Dynamic testing procedure

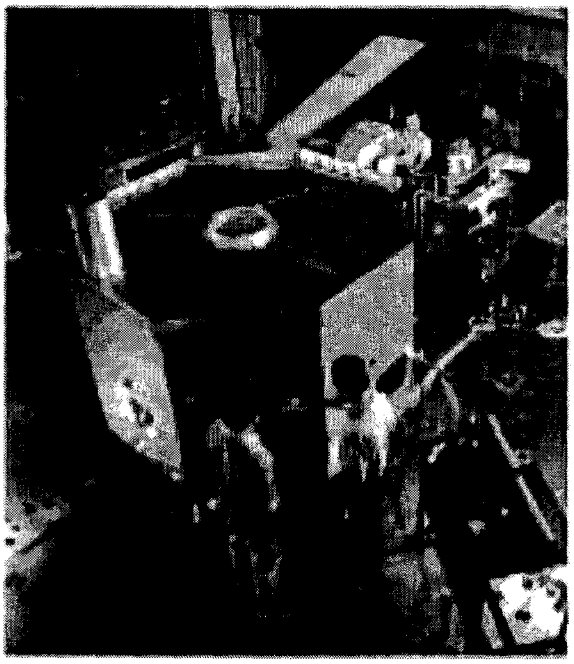
2.1 Ground Vibration Test

Ground Vibration Tests (GVT) are needed on all new aircraft types – or after major modifications of existing models. Its first objective is to verify models used for the calculation and prediction of the dynamic behavior of the structure. Flutter prediction is the first concern for the safety and certification of the aeroelastic behavior of an aircraft, but other dynamic aspects, such as sustained vibration due to engine unbalance, need verification. The main target of the tests is to identify the different modes of vibration of the aircraft, as well as their frequency, damping and scaling characteristics. Additional verification on the linear characteristics of these parameters is also required. These types of tests, performed for many decades now, were the driving force for the development of "modal analysis", a technology which was the foundation of LMS.

2.2 Modal Survey Test

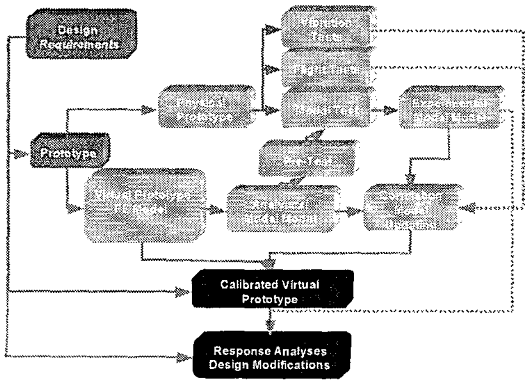
Satellites are subject to tremendous vibration and acoustic loads during their launch Space hardware development programs typically foresee two phases requiring laboratory tests. First a so-called modal survey is carried out to obtain an experimental dynamics model of the structure or to update a

Finite Element (FE) model. These models are essential in planning the second phase, namely the qualification test. Here, the structure is subjected to environments that are representative for flight or launch conditions.



2.3 The Integrated Approach

The Ground Vibration or Modal Survey Tests are very similar in nature and requirements. LMS offers a family of integrated software tools that performs all the steps from test preparation to test data exploitation. These tools will fit perfectly in the total process required for the validation of the structure.



2.3.1 Test Preparation and Test Planning

For all major aerospace development projects, the Finite Element Model is a crucial element used in the prediction of the performance of the structure. But it also provides invaluable information that can help to plan the test in a more efficient way. The LMS CAE Gateway allows the use of this FE model in the preparation phase of the modal test. The Pre-test module will help both CAE and test engineer in their tasks:

- Direct access to FE-model and results (mode shapes) in its original format
- Selection tools of target modes, e.g. the modes which are most critical for flutter
- Automatic or manual selection of optimal number and location of vibration transducers to increase the observability of the modes
- Optimum selection of shaker positions in order to excite all target modes
- Easy creation of test geometry and visualization of FE-modes on this reduced geometry
- Preparation of a set of active nodes for later Test-FE correlation
- Synthesis of Frequency Response Functions, to simulate test results

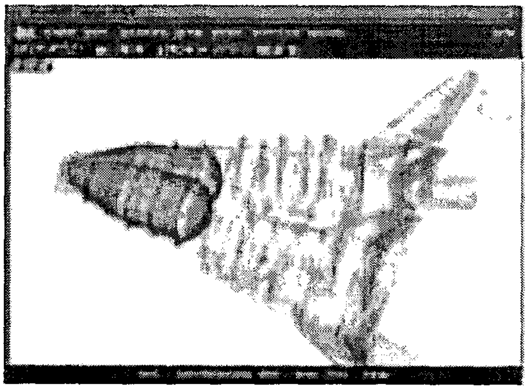
This results in the possibility to do the test with less transducer, to reduce instrumentation set-up time, and to avoid costly re-equipment work.

2.3.2 Test Equipment

The necessary test equipment consists of different components:

- Aircraft suspension
- Excitation equipment (shakers, amplifiers, shaker attachments, ...)
- Transducers (force transducers, accelerometers, cables, signal conditioning, ...)
- Data acquisition system, typically consisting of a data acquisition frontend connected to software running on a workstation (PC or Unix). The data acquisition system itself will typically do the signal

conditioning, data acquisition and processing, as well as signal generation and control.



Thanks to its experience as a provider of systems and engineering services, LMS can offer solutions covering all these aspects.

A typical configuration will look as follows:

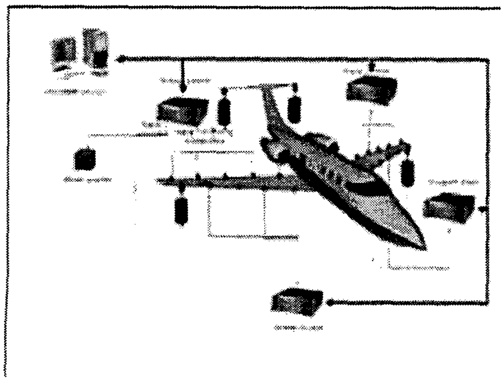
• A high-end PC

• A 256 channel SCADAS III, consisting of 4 frames for full flexibility, 8 signal generator channels (output channels) to drive the shakers, and 256 measurement channels (input channels) to measure input forces and response accelerations.. Measurement channels should include at least

Voltage and ICP® signal conditioning and ideally also TEDS support.

• software for test-preparation, for data acquisition (supporting different test strategies), for data-processing, and for Test-FE correlation and updating

The different components will be explained further. The system is fundamentally flexible; adaptations to the specific requirements of the customer are possible.



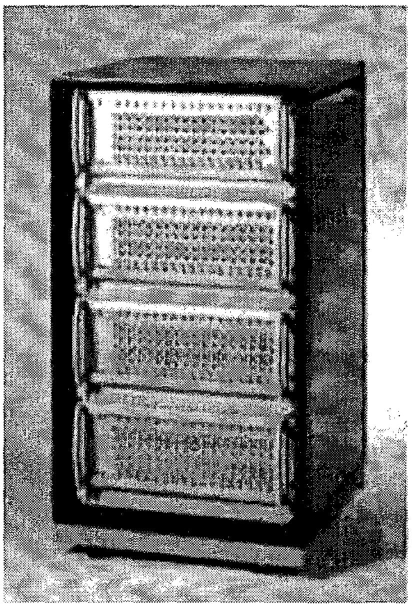
2.3.3 Data Acquisition Front-end

LMS offers a state-of-the-art high-quality, high-reliability front-end, that gives the usability, performance, and flexibility that is required for typical ground vibration or modal survey tests, which typically include a large number of channels.

The LMS SCADAS III is a multi-channel digital data-acquisition front-end system that will do both signal generation (output channels) as well as response measurements (input channels). It consists of one master frame connected to the host PC or workstation from where the whole acquisition is controlled. The interface is a standard SCSI connection allowing highspeed communication and data transfer between front-end and workstation. The master frame can be further connected, through a single master/slave cable to up to 20 slave frames. Each frame contains up to 68 parallel input channels. The input channels are available in modules of 4 channels, consisting of one DSP board with 16-bit sigma-delta ADC converters and 204.8kHz sampling frequency for each channel, and a four channel signal conditioning module. Signal Conditioning modules are independent from the digitizer cards; for optimum flexibility between different transducer types, two or more signal conditioners (e.g. an ICP® and a charge amplifier type of input) can be connected to the same digitizer card.

The architecture allows to distribute the frames around the aircraft. The transducers will be connected to these frames, and the frames themselves are connected to the workstation through a single cable. This reduces the need for long cables and improves the signal to noise ratio. The ICP® cable check visible with an LED on the input channel, makes physical connection and testing of the connection much easier.

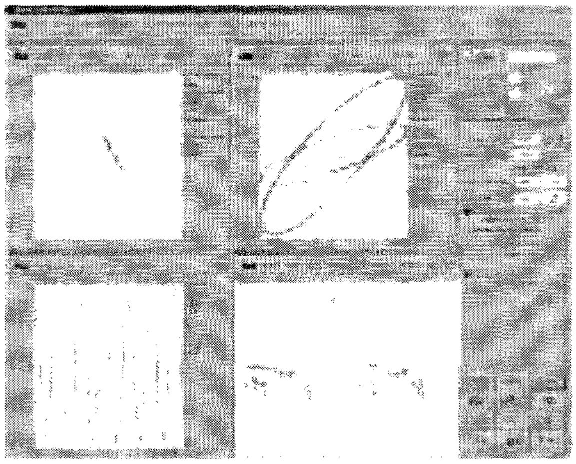
An additional possibility to reduce setup errors and minimize test time is through the use of "Smart sensors". Smart transducers are the latest development in transducer technology. These transducers



have an embedded memory chip that stores important information such as manufacturer name, serial number, calibration value and even geometrical data on-board. Today, classical ICP® transducer types are optionally available with a "TEDS" or Transducer Electronic Data Sheet inside the transducer (compliant with the preliminary IEEE 1451.4 standard). When using such transducers, the LMS solution offers the unique possibility to read in the transducer information directly through the SCADAS III into the data-acquisition software and automatically generates the geometry model based on the information stored in the transducer. No external device is required. The resulting configuration is extremely simple and minimizes the risk of any human error. Anybody who has some practical experience of conducting such a test knows that such errors are the major sources of lost time doing frustrating test-setup troubleshooting.

2.3.4 Testing Methods

Two types of testing methods exist to identify the modal parameters: phase resonance testing and phase separation testing.



Phase Resonance Method

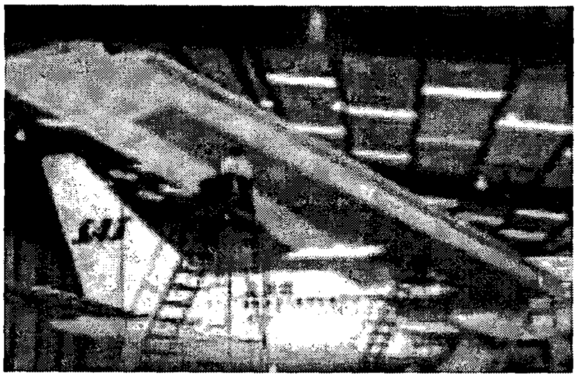
The phase resonance method has been used for decades to identify the modal parameters of air- or spacecraft structures. The modes are identified by applying a harmonic excitation with a specific amplitude and phase distribution at several input locations on the structure at the resonance frequency of a mode. The "art" of doing a phase resonance test consists in finding the best shaker locations, determining the required force distribution, controlling the input forces and searching for the resonance frequency. This method is known to be the most accurate method for a good identification on large structures. It has the capability, with an appropriate choice of shaker location, to isolate difficult modes and gives the possibility to qualify the nonlinear behavior of the structure. However it can be very time-consuming compared to the some phase separation methods such as the multiple input random excitation method.

Phase Separation Method

The Phase separation method has been introduced with the Fourier analyzers and the computer controlled measurement systems. The modes are typically identified in a 2-step procedure. In the first step, the dynamic characteristics of the structure are measured in terms of "Frequency Response Functions" (FRFs), which represent an inputoutput relationship in the frequency domain. Those measurements are done with either a broadband excitation such as an impact measurement or a random type of excitation, or with a swept or stepped sine excitation, covering the complete frequency range of interest. In the second step the required modal parameters (frequency, damping, mode shape and mode shape scaling) are identified from this set of FRFs using sophisticated parameter identification or "curve-fit" routines. An important advantage of this approach compared with the phase resonance method is the speed. It typically allows a reduction of the test time with a factor of up to 10, depending on the number of modes that need to be identified.

Combining Test Methods

Given the current pressure on reduction of the total test time for the Ground Vibration Tests or Modal Survey Tests, the current approach is very often a combined approach.

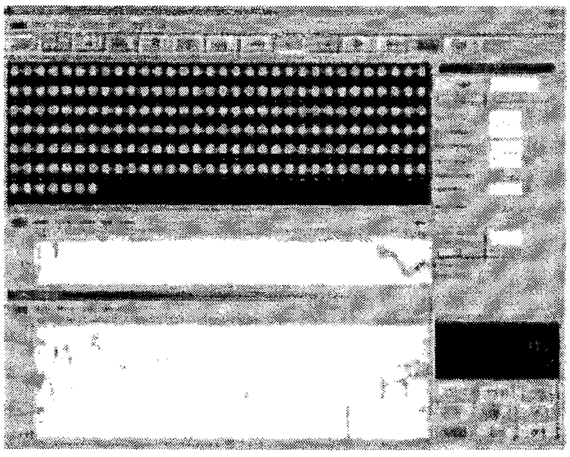


First, the airplane will be measured with a multiple input broadband excitation (e.g. burst random), using the information from the "Pre-test". Then, the most critical modes for the flutter phenomenon, or modes that were difficult to identify with broadband excitation, will be identified with a phase resonance test. For certain type of aircraft or structures, the impact method, which is the quickest, might even be used. In addition, due to the increasing importance put by the certification authorities on the problem of sustained engine rotor imbalance conditions (e.g. windmilling, a phenomenon which can occur in aero-engines after a fan-blade has come off during flight), special test requirements might exist for the measurement of FRF between the engines and the complete airframe, using e.g. a stepped sine excitation.

The LMS system gives the flexibility to quickly switch between all these test methods, using the same equipment. All relevant information concerning the setup, such as channel definition tables are common to all applications.

Multiple Input Random excitation

The best method for the measurement of as many modes as possible, is the random type of excitation. For such a test, it is important to be able to use different shakers simultaneously, as this will guarantee a better energy distribution over the system. Excitation such as burst-random or periodic random are considered as the best methods, as they remove the problem of leakage caused by FFT



However, in order to guarantee qualitative data when doing a multiple input random test, it is important to check that the different excitation forces are not correlated with each other. The LMS system will do this easily as part of the setup verification. As with any other type of test, during the test the data quality will be monitored for overload condition or bad cable connections. An LED indicator on the front-end itself allows the easy location of the physical channels associated to the problem, while a software

LED display gives a complete overview of all channels on the computer display. During the acquisition, the display of the measurements remains completely interactive, allowing the operator to view other channels. Data quality verification procedures include visual inspection of all the coherence functions and FRF's and a very quick global verification of correct transducer operation and positions can be done immediately after the test by visualizing the deformation shape e.g. at a frequency below the first flexible mode. By animating the difference between the measured deformation shape and the theoretical rigid body motion, remaining transducer or cabling errors are easily identified.

Multiple Input Stepped Sine

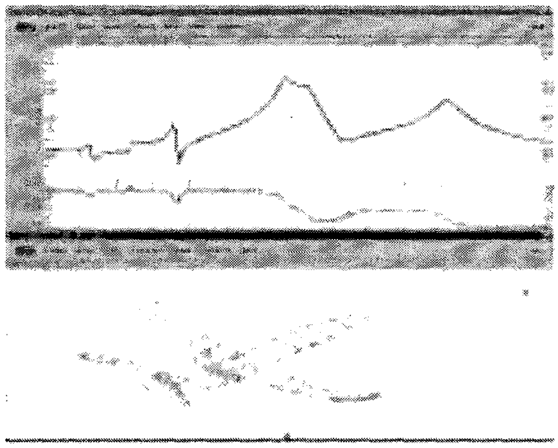
MIMO stepped sine testing is based on the simultaneous excitation of the aircraft through a multi-exciter configuration, loading the structure with uncorrelated stepped sine excitation. It provides either MIMO FRFs to be used in the modal analysis phase or response spectra for a specific harmonic loading. For the latter, MIMO control of the input forces, with a feedback control is required. It offers highest dynamic range by full use of the ADC at each excitation frequency. Test efficiency is increased by defining several frequency ranges with the most appropriate frequency resolution. For a non-linearity study, a sequence of tests at different levels of excitation can be defined and executed automatically. The unfiltered time signal or the Total Harmonic Distortion can be saved for later study of the non-linearities. As the frequency will gradually increase, the deformation shape at any moment will be animated on the display, again an additional cross-check on data quality.

Impact Testing

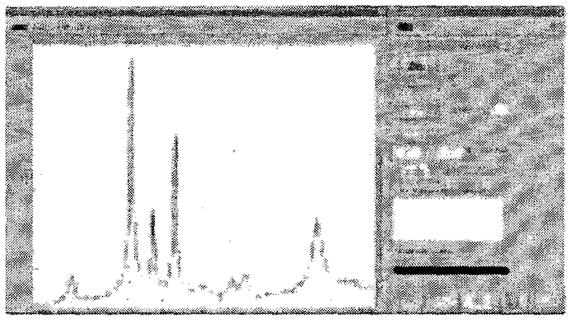
FRF's can also measured with an impact test. This is particularly useful for a quick evaluation, e.g. for a verification of the behavior of the control surfaces. Important for the efficiency of such a test is the capability to determine the trigger condition for the impact very easily, to have very clear visual and if necessary also audio feedback on the status of the measurements (e.g. waiting for trigger, triggered, overload,...)and the possibility to accept or reject individual measurements.

Identification Methods

The FRF's obtained through the different testing methods are fed into modal parameter



estimators. For a very quick validation, the Complex Mode Indicator Function Method (CMIF) will extract the dominant mode shapes frequencies and damping values with minimal user interaction. For more detailed analysis, advanced multi-reference, multiple degree of freedom methods are available. The Polyreference or multi-reference Least Squares Complex exponential method is one of the fastest and very widely used methods. For identification of highly damped modes,



a frequency method such as the Frequency Domain Direct Parameter Identification provides excellent results. Tools such as the Mode Indicator Function, the automatic summation of all FRF's, the stabilization diagram with immediate mode shape visualization, are essential in the identification process.

New parameter identification methods have been developed, such as the "Least Square Complex Frequency Domain" method (LSCF), which provides a stabilization diagram in which almost all "spurious" or "mathematical" poles have disappeared, making the identification process much easier. Another interesting method is the maximum likelihood estimator (MLE), a method that can take additional information on measurement noise into account and thus provide confidence intervals on the estimated modal parameters. All these different methods are available with a very interactive and intuitive graphical user interface, making the identification process as simple as possible without compromising the accuracy and reliability of the results.

Mode Tuning

As mentioned above, most of the modes can be identified with the phase separation technique. Particular modes can be acquired with higher precision using the phase resonance method. The first step for this approach will be the choice of exciter location and the determination of required amplitude and phase of the force to be applied at each input location. The LMS system calculates these values, based on FRF measured with the random or sine, or calculated from the Finite Element model. Besides the more classical Asher method, the Mode Indicator Method, or even the Inverse Mode Indicator Method is particularly robust and easy to use, as it can include all response channels and not just the driving point responses. The calculation is integrated in the normal mode tuning procedure.

During the tuning, the system typically displays Lissajous plots of the response channels versus the input force channels. At any moment the deformation of the structure can be animated on the display, either in a complex format or in a format where inphase response and total response are separated. Of course, as for other type of measurements, the display can be interactively modified to view other channels, to view in different formats (e.g. scatter display of all responses or parts of responses), bar chart display of level and phase, on-line calculation of a quality indicator such as the Mode Indicator function.

Both automatic and manual tuning are available.

The LMS system has a feedback control that compensates for cross-coupling between the generated voltages going to the shaker amplifiers and the applied forces. It also provides the capability to recalculate, during the tuning process, a new force appropriation, again based on the Inverse Mode Indicator Function Method. The mode will be tuned once the frequency and amplitude/phase distribution of exciter have been found which creates a vibration of the structure where all response points move "in quadrature" with the input forces.

For the estimation of generalized parameters such as the modal damping and modal mass, the LMS system provides the "Complex Power Method" in an on-line mode, which allows having the results immediately after the micro-sweep around the resonance. Other methods like the "Force in Quadrature" or any other "classical" parameter identification method on the obtained Single Degree of Freedom response around resonance are possible – and will increase the confidence in the obtained values.

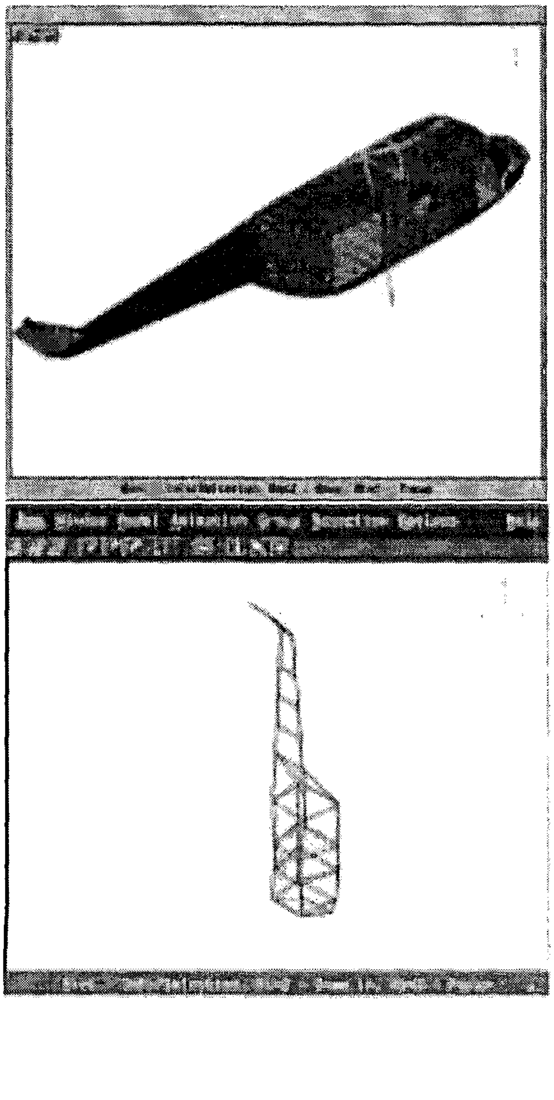
2.3.5 Validation Tools

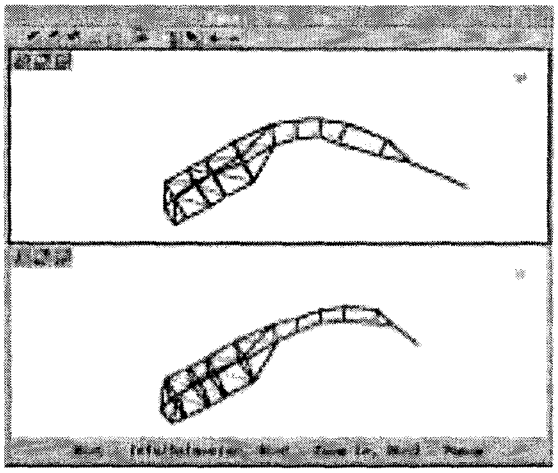
The last, but not least important step in the modal identification process is the validation of the results. The LMS solution offers the widest range of validation tools, including on- or offline FRF synthesis, Direct Mode shape animation, Modal Assurance Criterion, Mode complexity, Modal Phase colineareity, reciprocity check, rigid body decomposition, etc...

2.3.6 Test and FE-model correlation and Updating

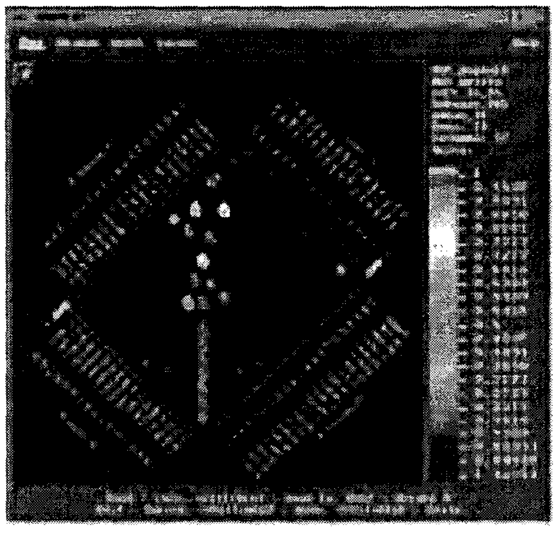
Once the measurements are done, the next step is the validation of the Dynamic Finite Element Model.

Typical steps include: the integration of Test and Finite Element Model in one common database; correlation of Test and FEM geometry (this step is simplified in case the FE model has been used for the pre-test); modal and FRF based correlation analysis to evaluate the correspondence of the test results with the Finite element results; and Finite Element Model Updating, using either Modal or FRF based sensitivity analysis. The LMS CAE Gateway provides an environment where all these operations can be done very easily, with direct access to both the test and FE element results, and with powerful





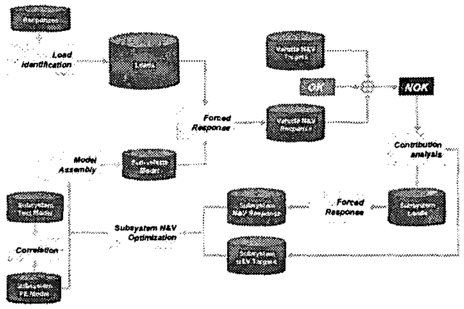
dedicated visualization and graphical selection tools. Discrepancies between the test and FE results are visualized and quantified, and modeling errors detected. If the FE model needs to be modified, the appropriate zones for this modification are determined using sensitivity calculation toward natural frequencies, total mass, proportional or physical parameters. Modal updating solver and Sensitivity calculations can be independent of the FE code, or be integrated with e.g. MSC.Nastran Sol200. Seamless integration is realized Access to the binary results file and automatic creation of updated input file



2.3.7 Design Modifications and Response calculations

With the updated model file, further

refinement, response calculations on several design alternatives can easily be done and compared within the same environment.



2.3.8 Flight tests

In addition to the identification of the modes during a ground vibration or modal survey tests, the dynamic behavior of the system during flight will need to be identified. For aircraft, these are the typical "flutter tests", for spacecraft, it can be post-flight identification, allowing updating the model for future launches. Within the same software platform, using the same data format that allows easy transfer of information and comparison of results, LMS has two modules for these kinds of analyses:

• the "flutter analysis" module measures the data during the flight flutter test and analyzes it in a streamlined way

• the "Operational Modal Analysis" module provides the latest developments, such as subspace identification techniques, which allows to do a very detailed analysis of the flight results resulting in the frequency, damping and modeshapes of the structure during the flight.

2.4 Vibration Qualification Tests (Vibration Control)

The SCADAS III front-end is also perfectly suited for the vibration qualification tests where the structure is submitted to vibration profiles in random, shock, sine or combined mode. For such tests, next to test performance, safety is critical, as the vibration levels to which the structure is submitted can be extremely high. Customers choosing for an LMS solution will benefit from the interoperability of their hard- and software and thus make better use of their investment.

3. 결 론

The critical factors needed to achieve a better and shorter test results, are:

- Appropriate use of FE-data for test preparation
- Flexibility for the test system and testing techniques
- Early detection of testing errors through different data validation procedures
- State-of-the art test data analysis tools
- Tight integration of test results with Finite Element data to verify and update the FE model.

As a partner that can deliver innovative total solutions, including testing and modeling, hardware, software and engineering services, LMS will team with you to help you to achieve the necessary improvement in the dynamic testing of aerospace structures.

4. Continuous Research

LMS makes significant investments in continuous research & development.

The European research project "Synopsis" successfully helped the development and validation of parameter identification routines for "In Operation Modal Analysis".

Applications include flight measurements for fixed and rotary wing aircraft and space launch vehicles. With the work and experience gained within this project, the product "Operational Modal Analysis", was developed, being the first commercially available product for such kind of analysis.

Partners of the project were LMS International (project coordinator), SAAB (SW), SOPEMEA (FR), PZL-Swidnik (PL), ISMC (BE), KULeuven (BE), INRIA (FR), Ecole Centrale de Paris (FR), University of Krakow (PL), Predictive Control (UK), Victoria Manchester University (UK).

Project "Helisafe", finished in 2001, had as an objective the development and industrial