USING MSC/NASTRAN AND LMS/PRETEST TO FIND AN OPTIMAL SENSOR PLACEMENT FOR MODAL IDENTIFICATION AND CORRELATION OF AEROSPACE STRUCTURES

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Abstract

As time-to-market also in aerospace begins to play a crucial role, accurate predictions and simulations of the behavior of new structures based on analytical models become more and more important. A modal identification must be performed to obtain modal parameters which can be compared with the pre-test analytical results using correlation techniques. Based on the outcome of the correlation analysis, the analytical models must be 'updated' such that they more accurately predict the actual test results. Since often the time is lacking to validate each component separately, it is a great challenge to define an optimal sensor set for the complete assembly, including internal components. Also, new materials, hyper-new design and not to forget the ever growing model sizes do not make the job more easy. This paper approaches the sensor placement problem from the standpoint of the structural dynamicist who must use the modal parameters obtained during a ground vibration, or eventually an on-orbit test, to perform a test-analysis correlation and updating analysis. The paper also explains which tools are available to make his life easier. A good choice is crucial not only for experimental observability of the dynamic behavior of the structure, but also for the accuracy of the reduced matrices (for orthogonality calculations). Eventually it will help also the modal analysist during his tests and it will make the (often-difficult) geometric correlation obsolete.

Introduction

The objective of an effective integration of finite element analysis with structural testing is to combine the advantages of both approaches in a more valuable synergistic approach. The analytical approach is predictive and can be used for predicting the flight loads and assessing the structural integrity prior to the prototype production. The experimental approach, based on modal surveys on the prototype, observes the actual behavior of the structure under controlled laboratory (ground vibration test) or real operating conditions (in-flight testing). The benefits of such a combined approach are that:

- Testing provides reliable information to cross-check predicted FEA results (**Correlation Analysis**)

Testing can provide reliable estimates for system damping and resonance frequencies. Furthermore, analyzing the experimentally obtained mode shapes, and comparing them with the results from FEA, is critical in assessing the value of the analytical model and its interpretation. After the difficult geometry mapping (geometrical correlation) that aligns both topologies, several modal based assessment criteria are used to validate the analytical model. In aerospace, commonly used tools therefore are the Modal Assurance Criteria (MAC) and the Cross-Orthogonality Criteria.

Modal Assurance Criterion

The modal assurance criterion (MAC) is used to evaluate the correlation between two modes ignoring the effects of the system mass. It is an easy criterion and has been used primarily to check the independence of two modes.

$$[XMAC] = \frac{\left[[\Phi_a]^T[\Phi_t]\right] \otimes \left[[\Phi_a]^T[\Phi_t]\right]}{\left\{Diag\left([\Phi_a]^T[\Phi_a]\right)\right\}\left\{Diag\left([\Phi_t]^T[\Phi_t]\right)\right\}^T}$$

Cross-Orthogonality

The cross-orthogonality is used to identify the corresponding test mode that associates with an analytical mode, including the effects of system mass. A generally accepted requirement for the cross-orthogonality is to have all diagonal terms larger than 0.9 and all the off-diagonal terms less than 0.1.

$$[XOR] = [\Phi_a]^T[M_a][\Phi_t]$$

Since the outcome of the cross-orthogonality calculation is also dependent on the quality of the measured test modes, the orthogonality matrix of the test modes with respect to the analytical reduced mass matrix is used to assess the quality of thereof. The test data is acceptable if the off-diagonal terms of this orthogonality matrix are less then 0.1 when the diagonal terms are normalized to 1.0.

The requirement for modal frequencies of corresponding experimental and analytical modes is to have a discrepancy within 5%. If both criteria, cross-orthogonality and frequency discrepancy, are met, the analytical model is said to be test-verified.

This in-depth correlation analysis will provide understanding of the discrepancies between the analytical results and the test results, and will teach the designer how to improve his design.

- Testing results can be used to enhance the Analytical Model (**FEA model Updating**)

The outcome of the correlation analysis will decide if it is necessary to modify the analytical model so that it better describes the results observed from testing. An improved analytical model is obtained by changing analytical model parameters such that the discrepancy between test and FE resonance frequencies is minimized. Such a structural optimization (updating) can be performed using the MSC/NASTRAN Sol200 capability and thus are the changeable parameters shell thickness, beam cross-sections, spring stiffnesses and such.

- The FEA results can be used to better design the Test (**Pretest Analysis**)

FEA information can complement the Test Engineer's expertise in selecting optimal ways of stimulating and measuring the dynamic behavior of the test structure. Moreover, it will make the geometry mapping of both topologies trivial since the experimental geometry was originally created from the FEA model.

This synergistic approach consists thus of the following steps, see fig.1. :

1. FEA Modeling and Analysis, using MSC/PATRAN and MSC/NASTRAN
2. Pretest Analysis using MSC/NASTRAN and LMS/PRETEST
3. Modal Testing & Analysis using LMS CADA-X Modal
4. Correlation Analysis using LMS/Correlation and MSC/NastranForLink
5. FEM Model Updating using LMS/Updating and MSC/NASTRAN Sol200

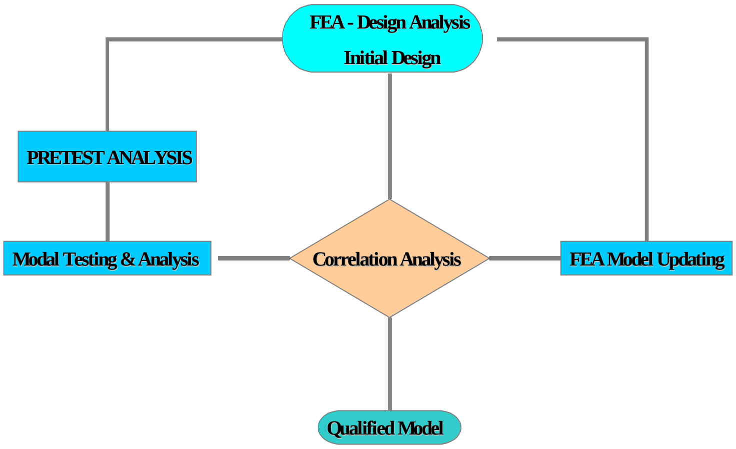


Figure 1: Linking Test and FE

From Pretest analysis to FEM Model updating

MSC/NASTRAN and LMS/PRETEST

A typical pre-test analysis will usually consist of different steps, see fig.2. Starting from a CAD model, an analytical model is created and the dynamic behavior is calculated in terms of resonance frequencies, mode shapes and system's mass and stiffness matrices. Out of all these modes, a limited set of target modes has to be selected and sensors and shakers have to be placed such that they efficiently capture and excite all of these target modes. Lots of techniques and methodologies have been developed already and are still being developed and most of them are implemented by means of user programming (DMAP) in MSC/NASTRAN.

Using both MSC/NASTRAN and LMS/PRETEST in combination offers the structural dynamicist an additional surplus because the outcome of most of his MSC/NASTRAN dynamic calculations becomes available for interpretation in nice displays at the same time. In addition to that, LMS/Pretest offers some additional tools.

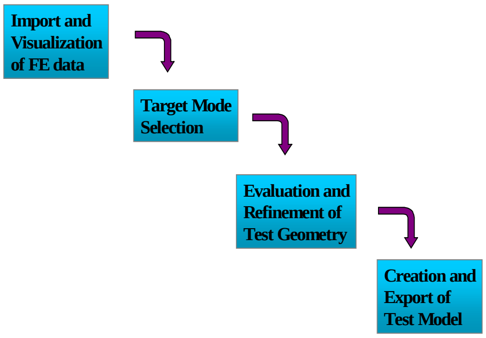


Figure 2: The different steps in a pre-test analysis.

If then finally the sensor and shaker locations are determined, an experimental geometry can be created and the necessary input files for the test engineer are written out.

Target Mode Selection

A first, very important step in the pre-test analysis is the selection of the target modes, especially since the modal density of launch vehicles and other aerospace structures within the frequency range of interest is usually very high. It is however not necessary to ‘capture’ all these closely spaced modes during a modal survey test, because only some of them will contribute significantly to the critical component responses. These critical responses are usually located in the areas of hardware concern.

These important structural modes are called ‘target’ modes, and their selection is critical for the generation of a validated analytical model. A test-verified model will, by definition, have a good correlation between the test target modes and the analytical target modes, but not necessarily for the non-target modes. It follows that a poor selection of the target modes could result in an analytical model, which would not accurately predict the structural responses and member loads.

Before any criteria are used to determine the target modes, all modes coming from an analytical modal analysis should be described in detail by a ‘simple’ visual inspection. This inspection gives the fundamental insight in the modal behavior of the structure and will also serve to interpret all used target mode selection criteria.

Generally, there are four methods or combinations thereof widely used in the aerospace industry. These are the rigid body modal effective mass, the constraint modal effective mass, the modal kinetic energy fraction and the modal strain energy fraction. Another method, which uses a somewhat different approach, is the use of modal participation factors. Besides these, also other techniques are reported already. [7],[4]

1. **Rigid Body Modal and Constraint Modal Effective Mass**.

The rigid body effective mass associated with each deformation mode represents the amount of system mass participating in that mode. Therefore, a mode with a large effective mass is usually a significant contributor to the system’s response. These criteria are in other words used to find the important system modes. A typical requirement for the selection of target modes is that modes with a translational effective mass equal to or greater than 2 percent of the total mass are target modes. If the modes are calculated using mass normalization, the formula becomes:

$$Meff = \left[[\Phi_d]^T [M_s][\Phi_{rb}] \right]^2$$

Note that this is the same as the root of the mass orthogonality between the deformation modes and the rigid body modes.

The constraint modal effective mass is similar to the rigid body modal effective mass, but the constraint modes are used instead of the rigid body modes. This formula makes more sense if the component (e.g. payload) is over constrained.

2. **Kinetic/Strain Energy and Kinetic/Strain Energy Fraction.**

Since the modal effective mass criteria look at the structure’s dynamic behavior on a global basis, they are usually able to identify the important system modes but they are less useful for the determination of important local modes. To include the significant local modes of a subsystem for improving the response prediction, the kinetic and/or strain energy fraction of that subsystem is calculated. The kinetic energy fraction is defined as the amount of kinetic energy in that subsystem relative to that of the whole system. The selection criterion to consider a component mode as target mode is an energy content of 50% of the total system energy. These target modes will be added to the target mode set if not yet been selected by the previous criteria. If the modes are again mass normalized the formula for the kinetic energy fraction becomes.

$$KEF = \frac{Diag\left([\Phi_c]^T [M_c][\Phi_c]\right)}{Diag\left([\Phi_s]^T [M_s][\Phi_s]\right)} = Diag\left([\Phi_c]^T [M_c][\Phi_c]\right)$$

The kinetic energy fraction for the first deformation mode of a scale model of a Boeing 747 is shows in Fig.4 on top of the geometry. The fuselage, both wings including engines and the tail wings are clearly visible as being the different components. Ultimately, it is possible to visualize the kinetic energy of each element in model separately, see Fig.3.

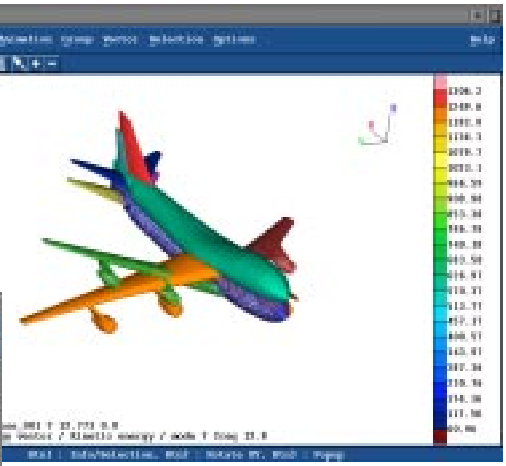


Figure 4: The modal kinetic energy for the first deformation mode for several parts of a Boeing 747. The lower plane is the undeforrmed mode shape and each color represents a different group.

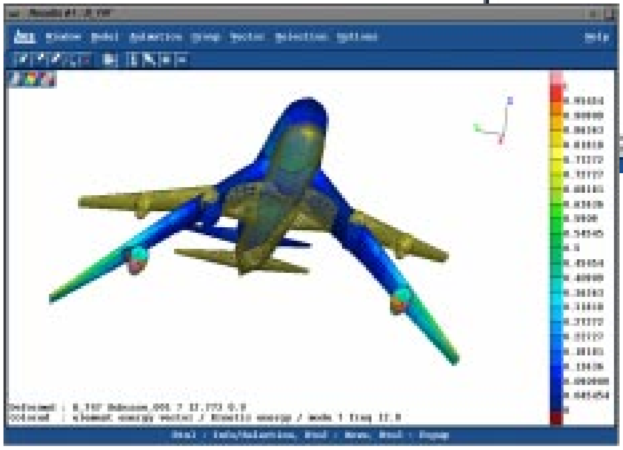


Figure 3: The modal kinetic energy for the first deformation mode for each element separately.

3. Mode Participation Factors.

Although the previous methods may identify the most of the target modes, some relevant modes critical to the payload or component responses may not be selected because none of them takes the excitation into account. The structural integrity depends not only on the structure's resonance frequencies, the mode shapes and the damping, but also on the frequency characteristics of the excitations. Therefore, a tool that includes the excitation characteristics in the target mode selection process will ensure the completeness of the target mode set. Useful in this context are the mode participation factors, which are calculated during the dynamic solution sequences, defined as (if mass normalization is used):

$$PF_i = \frac{[\Phi]^T F_i}{\left[\lambda_s^2 - \omega^2\right]}$$

The output is related to these participation factors by:

$$\{V\} = \sum_{i=1}^{N} PF_i \cdot \{\Phi_i\}$$

Important is that these participation factors are independent of the output. The participation factor is frequency dependant and its amplitude is determined by the structure's resonance behavior (for ω close to λ_s) and by the excitation spectra (for ω far from λ_s), as can be seen in Fig.6, for the PF of the first five modes. Plotting the participation factors of all modes for a certain frequency band of interest results in the colormap diagram of Fig.5. It is now easy to investigate if some modes are still being missed in the target mode set.

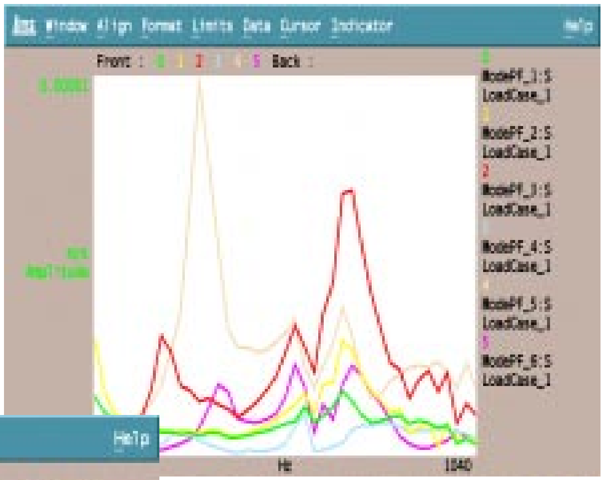


Figure 6: The first five PF. On the x-axis the frequency bandwidth, on the y-axis the amplitude of the PF.

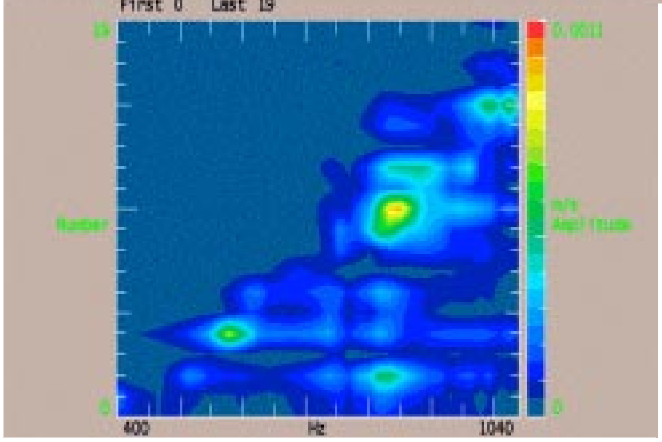


Figure 5: The PF for each mode (each vertical line is a PF) in a colormap display.

Sensor Placement

Once the set of target modes has been defined, the measurement locations and their corresponding degrees of freedom have to be chosen such that all target modes can be observed by the modal survey test. This can be extremely though for large space structures where the target modes can be closely spaced. Since it is not practical to instrument the test article in all degrees of freedom corresponding to those of the analytical model, the challenge is to use a minimal number of sensors, especially for in-flight testing, in order to sufficiently define the spatial resolution of all the target modes. An erroneous or too limited subset of sensor locations will lead to an incomplete geometric definition of the mode shapes, a phenomenon that is called ‘Spatial Aliasing’.

To asses the correlation of the mathematical model predictions which in general do not have dynamic degrees of freedom uniquely one to one with the modal test measurements, a reduction (usually Guyan) to the test-analysis model (TAM) is required. Since this dynamic reduction is done towards the measured degrees of freedom, the choice of the sensor set is also extremely important for the outcome and the interpretation of the dynamic correlation tools.

Since the analytical model sizes of complete assemblies are way too big for a manual selection of the sensor locations, a systematic approach in which the test engineer’s experience is central, see fig.

7, must thus be used. First a sensor set is searched to meet the observability criterion. This set is then eventually modified to obtain a qualitative TAM model.

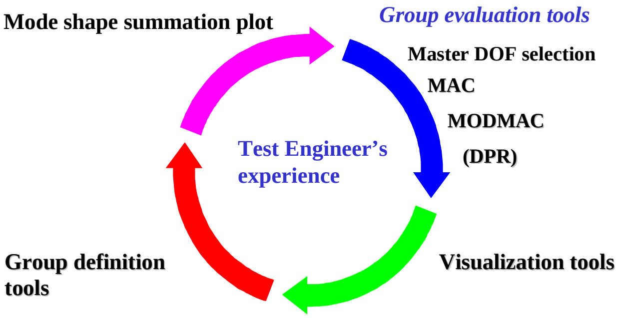


Figure 7: Systematic approach to find the optimal sensor (and shaker) set

1. Sensor set definition to meet the observability criterion.

The methodology used to evaluate the quality of a possible subset of the available analytical nodes and their corresponding degrees of freedom, usually all three translational degrees of freedom, is a Modal Assurance Criterion (MAC) calculation. If the off-diagonal terms of this MAC matrix are smaller than 0.1 à 0.2, the cross-correlation between the target modes is sufficiently low and the chosen set of measurement point will be able to observe all target modes.

If the initial group of points is not able to discriminate all target modes, a maximum off-diagonality MAC (MODMAC) can be launched. This algorithm aims at the completion of the initial subset with extra points/degrees of freedom that are chosen out of an additional subset such that a resulting group of points/degrees of freedom is kept that, given a set of target modes, shows off-diagonal MAC values below a given threshold. The initial group, the additional group and the target modes are the only input to this algorithm.

Although MAC and MODMAC calculations are straightforward and powerful, the results and especially the final amount of sensors still depend on the quality of the selection of initial and additional set of possible measurement points. Different tools may assist the test engineer's experience in the selection of those groups.

- **Master DOF Selection – Geometrical Spread**.

This tool constructs a group with a user-specified number of nodes that are maximally spread out over the structure. The spreading can be performed either on all nodes of the structure, as is illustrated in fig.8. where 50 points are spread out over the outer shell of the X-33 Advanced Technology Demonstrator. To avoid the risk of clustering, it is possible to ask for a minimal distance between the chosen locations. If a lot of component target modes were selected, it is also necessary to have a sensor distribution on these components. Fig.9 shows a spread of nodes on the internal LO2 tanks of the X-33.

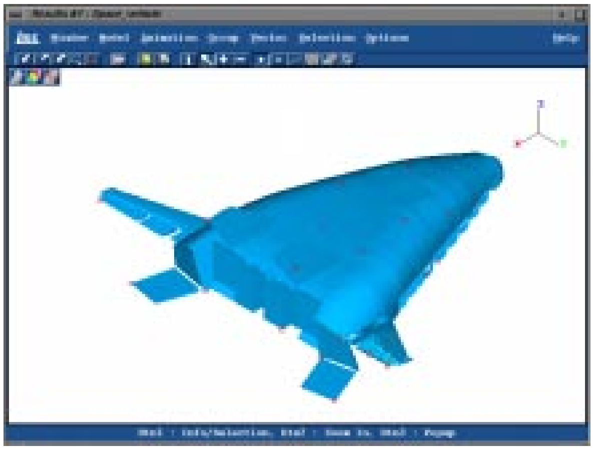


Figure 8: 50 nodes (triax) spread of the whole structure of the X-33 Reusable Launch Vehicle.

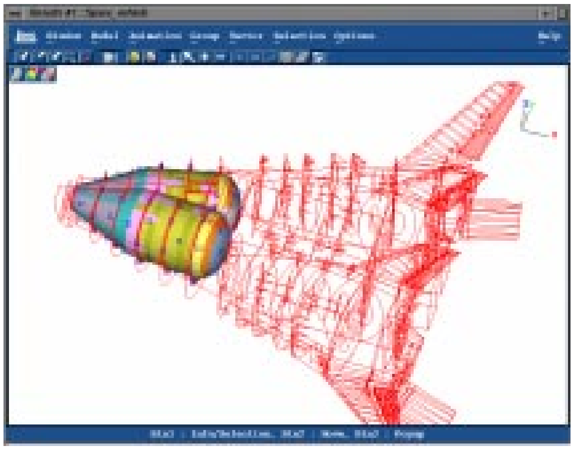


Figure 9: 50 points spread on an internal tank of the X-33. A character line wireframe gives the position of the tank in the whole model.

- **Mode Shape Summation.**

This tools calculates the sum of a set or subset of (target) modes and for this set of modes and within the selected nodes (assembly or component), a user-specified number of nodes with the highest (summed) deformation will be grouped. An example for a part of a satellite is shown in fig. 10. The summed mode shape is shown together with the two most moving points.

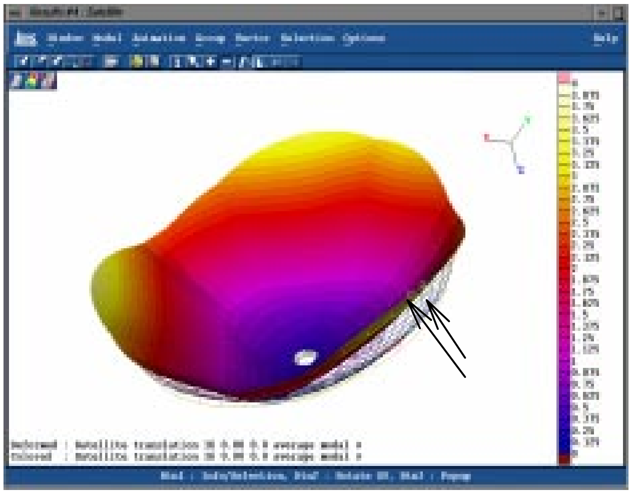


Figure 10: The summed mode shape (in color and deformation) together with the undeformed mesh. Two points were asked as output.

- **Group definition tools.**

Of course also different tools are available such as manual group creation and editing, creation of groups by clicking points in the geometry, grouping all nodes that correspond with a certain element type…

A possible strategy to find an optimal set of measurement points can be starting with a relative small number of a-priori know response locations and launching a MODMAC with as additional group a spread of points over the structure. If the target threshold cannot be reached, for instance because there are local component modes amongst the target modes, a second MODMAC can be launched with an additional group that contains a spread of points only of that component…

2. Sensor set definition to meet also the cross-orthogonality criterion

Once a set of possible measurement locations is found that meets the observability criterion, one still has to check if this set of points can be used to obtain a high quality TAM model, by performing the actual reduction in MSC/NASTRAN. If we suppose Guyan reduction, one can check if the mass distribution by the calculation of the orthogonality between the spatially reduced modes and the Guyan reduced mass matrix.

$$[XOR] = [\Phi]^T \cdot \left[M^{TAM}\right] \cdot [\Phi]$$

An example is given in fig 11. The target put forward for this orthogonality matrix is that the diagonal terms are larger than 0.9, and the off-diagonal terms are smaller than 0.1 Therefore, the TAM model produced by the chosen set of measurement points in the example, is only valid for the first 13 modes. (including the 6 rigid body modes).

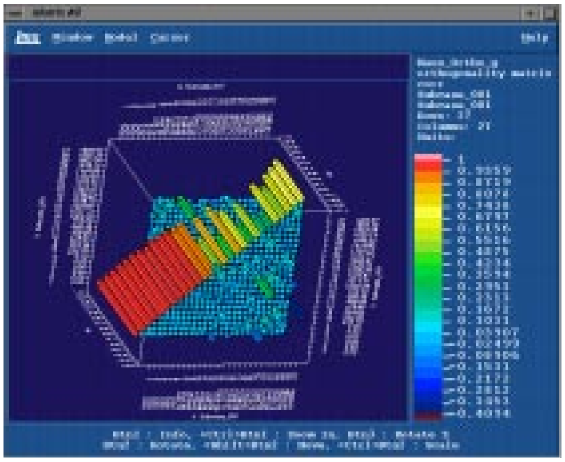
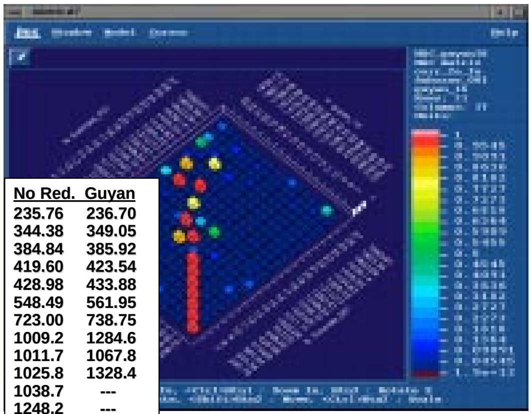


Figure 11: Cross-Orthogonality using original modes and Guyan reduced mass *matrix.*

It is also necessary to check if the modes from the TAM model are similar to the original target modes. The correlation between the original target modes and the reduced TAM modes and the resonance frequency discrepancy can be investigated using a MAC calculation. Typical for Guyan reduction is that the reduction deteriorates for higher frequencies, as can be seen also in the example of fig 12. It is obvious that the current set of measurement points is only valid for the first 7 target modes, although it is possible that more target modes can be observed using this set.



No Red.	Guyan
235.76	236.70
344.38	349.05
384.84	385.92
419.60	423.54
428.98	433.88
548.49	561.95
723.00	738.75
1009.2	1284.6
1011.7	1067.8
1025.8	1328.4
1038.7	---
1248.2	---
1283.8	1768.4
1312.7	1476.4
1355.2	1881.1
1434.8	---
1445.5	1603.9
1639.1	---
1803.0	---
1805.3	---
1965.9	---

If the cross-orthogonality and modal assurance criteria are not met, it is possible to add some extra measurement points to the A-set. This process is more or less trial and error. If using Guyan reduction, it is however possible to use the following tools.

- **Master DOF selection – Ratio M/K**

This tool allows the creation of a group of nodes and corresponding degrees of that have the biggest values of Q, where Q is given by:

$$Q_{ii} = \frac{M_{ii}}{K_{ii}}$$

With M_{ii}, K_{ii} are in the case of triaxes the sum of M_{iix},M_{iiy},M_{iiz} and K_{iix},K_{iiy},K_{iiz} respectively. Since usually this will result in clusters of nodes, an option is available to ask for a minimal distance between the nodes. Such a set of points is believed to be a good A-set and can thus be used for the MODMAC calculation.

Shaker Positioning

The third stage in the pre-test analysis is the selection of the exciter locations out of the resulting group of measurement points in order to optimally stimulate all the modes of interest. If the structure were to be excited close to a node of a particular mode, the corresponding resonance would be difficult to observe in the measurement data, and the experimental modal model would be hard to identify.

The tool that is used in LMS/Pretest for the selection of excitation locations is the calculation of the '**driving point residues**' (DPR's). DPR's are stated to be equivalent to modal participation factors, and are a measure of how much each mode is excited, or participated in the overall response, at the driving point. As such also the modal participation factors in all possible measurement points can be used. The definition of the driving point residue, for mode k and node i, is:

$$DPR_k(i) = \frac{\Phi_{ik}^2}{2m_k\omega_k}$$

The degrees of freedom with maximum average DPR over all mode shapes are considered to be the best excitation dofs for the specific set of target modes. An example is given for a tail boom problem [5] of a helicopter. The averaged DPR for all target modes is given, and the amplitude and the direction of the red arrow show the best position and direction to place the shaker.

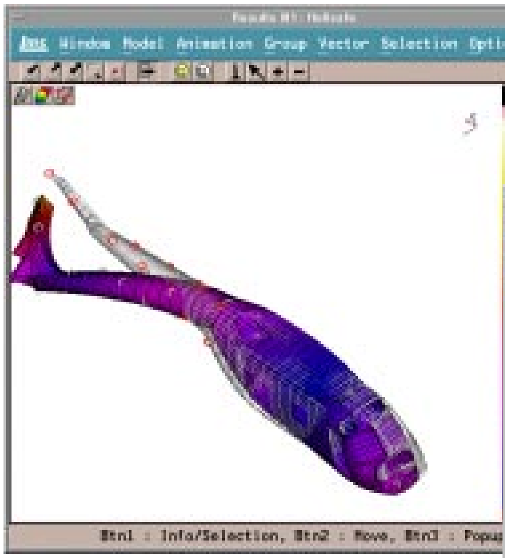


Figure 13: A typical tail boom mode together with the undeformed mesh.

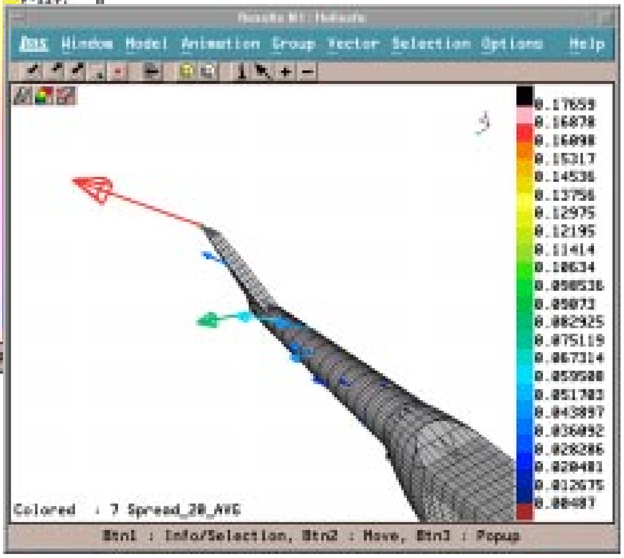


Figure 12: Averaged DPR for all possible excitation points.

Conclusion

Summarizing, this paper has tried to explain why a carefully performed pre-test analysis really is necessary to end-up with meaningful modal survey test results. Good test results are really a sine qua non for the interpretation of all dynamic correlation tools that are used in the analytical model verification and validation.

An overview is given of the commonly used techniques to address the target mode selection, the sensor location placement and the positioning of the exciters. It may be clear that the use of the available tools and the user programming capabilities of MSC/NASTRAN form a crucial aspect for the calculation of all described tools. The synergy of MSC/NASTRAN and LMS/Pretest gives the engineer the additional benefit that, a unique environment becomes available that guides the engineer through the complete process, from pre-test analysis over correlation to end up eventually at the model updating step, that the interpretation of the calculations can be visualized and that both program communicate directly with each other.

ACKNOWLEDGEMENTS

Many thanks to Lockheed-Martin for the use of the pictures of the X-33 finite element model and to the project INCO/COPERNICUS project No PL964283, HELISAFE, ”Model Based Improvement of Performance Maintainability and Reliability of Helicopter Structure”, supported by the EC, for their nice helicopter model.

REFERENCES

MSC PRODUCTS

(1) MSC/NASTRAN Basic Dynamic Analysis, Version 68, The MacNeal-Schwendler Corporation, Los Angeles, CA, 1993
(2) MSC/NASTRAN Quick Reference Guide, Version 68, The MacNeal-Schwendler Corporation, Los Angeles, CA, 1994

LMS PRODUCTS

(3) LMS CADA-X Manuals, Rev 3.5.A, LMS International, Belgium, 1998

CONFERENCE PAPERS

(4) Y.T. Chung, “Target Mode Selection based on load indicators”, Conference proceedings of IMAC-XVII, Florida, February 8-11, 1999
(5) T. Uhl, W. Bochniak, W. Lisowski, L. Hermans, H. Van der Auweraer, J. Malecki, “FE Model correlation of a helicopter using ground test results”, Conference proceedings of IMAC-XVII, Florida, February 8-11, 1999
(6) G.R. Parker, Ted L. Rose, J. J. Brown, “Kinetic energy calculation as an aid to instrumentation location in modal testing”
(7) Chung, Y.T., Semaker, M.L, Geradin, M., “Assessment of Target Mode Selection Criteria for Payload Modal Survey”, Conference proceedings of IMAC XII, Hawaii, pp. 272-279, 1994
(8) M. Brughmans, J.Leuridan, T. Van Langenhove, F. Turgay, “Validation of automotive component FE models by means of test-analysis correlation and updating”, Conference Proceedings of IMAC-XVII,Florida, February 8-11, 1999