Automatic modal analysis
Reality or myth?

ENGINEERING INNOVATION

Introduction

The increasing use of modal analysis as a standard tool means that both experienced and inexperienced analysts are faced with new challenges; uncertainty about the accuracy of results, inconsistency between estimates of different operators, the tedious task of selecting obvious poles in a stabilization diagram and the time-consuming iterations required to validate a modal model. LMS, as a leader in modal analysis, undertakes a continual quest to ameliorate these problems. LMS PolyMAX, for example exceeds other parameters estimation method with respect to the robustness of the estimator, and its ability to distinguish spurious from physical poles. Nevertheless, in the pursuit of automation, discrimination methods to distinguish physical from mathematical poles, in particular in the case of high-order and/or highly damped structures are unavoidable, resulting in highly operator-dependant results, and numerous iterations. This paper discusses the LMS PolyMAX parameters estimation method and the "AutoFit" curve fit expert system as a means of easing the burden of performing modal analysis in an appropriate and sustainable manner.

What makes automatic modal analysis possible?

The new Test.Lab Automatic Modal Parameter Selection (AMPS) tool is an intelligent rule-based technique to analyze the stabilization diagram by selecting only the physical poles, that was developed based on the observation of skilled engineers. It offers numerous advantages in that it is much faster, it allows less-experienced analysts to benefit from the knowledge and experience of experts, and since the method is deterministic it does not depend on the parameter estimation method used to obtain the stabilization diagram. It requires only one condition, which is that the stabilization diagram provides all the necessary information for selecting meaningful poles.

LMS Test.Lab PolyMAX, the latest generation parameter estimation method, with its crystal-clear stabilization diagram, answers this need perfectly. This therefore opens up the opportunity for automated pole selection in the most "natural" way capturing the decision process used by an experienced modal analyst and encapsulating it in rules that can be implemented as an autonomous procedure.

LMS Test.Lab PolyMAX

The LMS Test.Lab PolyMAX method uses measured FRFs as primary data whereas the least square complex exponential (LSCE) method uses impulse responses (obtained from the inverse Fourier transforms of the FRFs). Since LMS PolyMAX operates in the z-domain, it can deal with both highly damped and lightly damped structures. In addition, LMS PolyMAX does not suffer from the numerical instability and frequency range limitations caused by the higher model size and large frequency band associated with other frequency domain methods such as frequency domain direct parameter identification (FDPI) or the orthogonal polynomial techniques. The theory of LMS PolyMAX on classical modal analysis can be found in [5, 6].
It has been proven that the LMS PolyMAX estimator can also be used effectively in operational modal analysis. [10]

The crystal-clear stabilization diagram obtained by LMS Test.Lab PolyMAX is one of the key factors that make automatic poles selection possible, but it should also be considered as a general-purpose method for single broadband analysis of highly and lightly damped structures even with noisy data.

LMS Test.Lab Automatic Modal Parameter Selection (AMPS) tool

Some crucial factors demanded by modal analysts and engineers to improve the modal analysis process are:

- How to select poles in stabilization diagram
- How to speed up the iterative process of poles selection on stabilization diagram
- How to ensure that consistent analyses are obtained from different people from the same setup and measurement

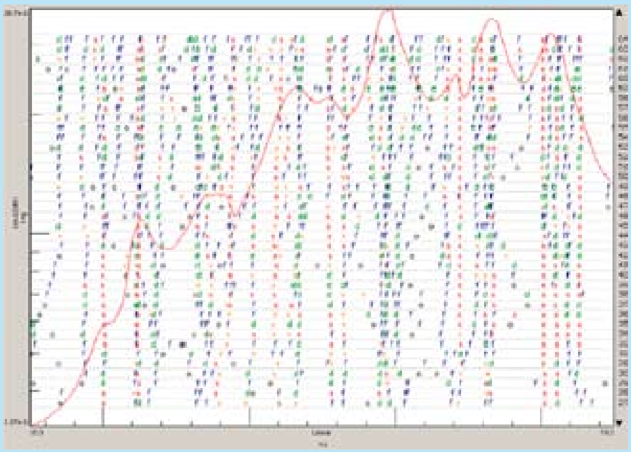


Figure 1. Stabilization diagram for a trimmed Body analyzed with LSCE

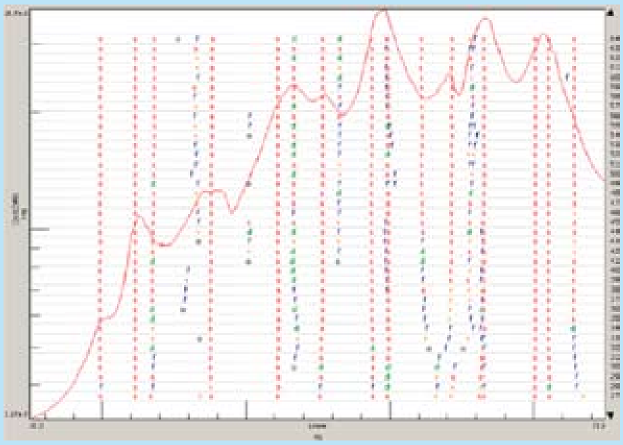


Figure2. Stabilization diagram for a trimmed Body analyzed with PolyMAX

How to select poles in stabilization diagram

Classically this has been done by an expert engineer visually inspecting the symbols in the stabilization diagrams, which are based on similarity in frequency, damping ratio and/or mode vector between poles belonging to subsequent model orders. In the first implementation of parameters estimation method such as least square complex exponential (LSCE) and frequency domain direct parameter identification (FDPI), the engineer was forced to select all the poles within the same model order to ensure mathematical consistency. Subsequently, as modal analysis was applied to ever more complex structures, it became obvious that due to the differences in modal density over the frequency range, the appropriate model order varies with frequency. It was then necessary to either merge estimations from different frequency bands in one analysis or to select poles from different modal orders within the same analysis. In a further step, the modal model built by these poles was checked with different validation criteria. This implicit knowledge is made explicit by casting it in rules used by the new Test.Lab Automatic Modal Parameter Selection (AMPS) tool.

Combining LMS Test.Lab PolyMAX method and the new Test.Lab Automatic Modal Parameter Selection (AMPS) tool not only ensures a user-independent result but also decreases the time consumed by the iterative process of pole selection on stabilization diagram resulting in consistent modal model between different users.

Proof-of-concept

A benchmark analysis was performed to evaluate the results derived from the new Test.Lab Automatic Modal Parameter Selection (AMPS) tool. The goal of the benchmark test was to provide a qualitative assessment of the AMPS tool, and to place it within the spectrum of novice to experienced modal analysts. Eight people were selected for the test, including 4 novices and 4 experts, all of whom had an engineering background. Two data sets were selected, and both were analyzed by every participant using two parameter estimation methods. The novices received a short description of the task they had to carry out:

1. The stabilization diagram shows poles – solutions of a mathematical problem – at different model orders. The task of the engineer is to select an – unknown – number of poles at different frequencies. Occurrence of a pole at the same frequency at increasing model orders gives the engineer information on the physical correspondence of this pole.
2. First, the engineer will look for a vertical column of poles. Especially if this column will contain lots of s-type (and d-type) poles. S-type means the pole's frequency, damping and pole vector are stable within the tolerances, d-type means the pole's frequency and damping do not change within the tolerance. It is not important that this column should exist at the lower model orders, nor that it is a straight column at the lower orders.
3. Next the engineer inspects the s-type and d-type poles in particularly, in which he values the s-type poles more than the d-type poles. The engineer searches for the pole in the column that is the most stable in frequency and which stabilizes in damping.

The first data set was a multiple-input multiple-output (MIMO) data set from a fully trimmed body of a car. It has 2 inputs and 264 measurement points distributed over the entire car body, leading to 528 FRFs. The parameter estimation was done with both a time domain method (LSCE) and a z-domain method (PolyMAX) for the frequency band 35–75Hz. Both stabilization diagrams were created to a model size of 64.

An initial examination of the two stabilization diagrams, shown in Figure 1 and Figure 2, show that the LSCE stabilization diagrams – the former standard – are rather complicated and clouded by spurious, mathematical, poles, especially at higher model orders, whereas the PolyMAX diagrams are quite distinct,

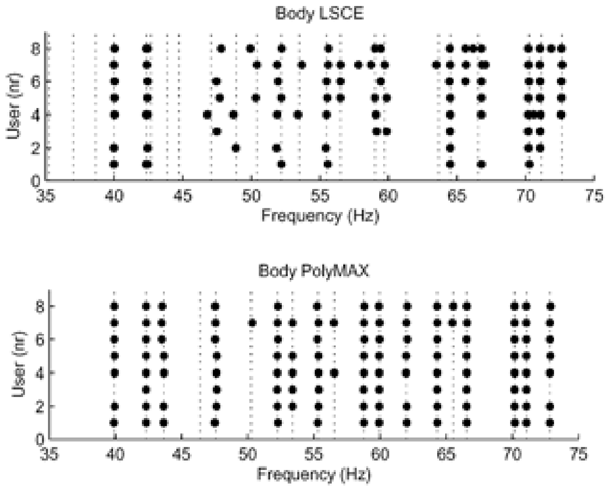


Figure 3. Body LSCE (top) and PolyMAX (bottom) pole selection per user, dotted lines represent poles selected by AMPS

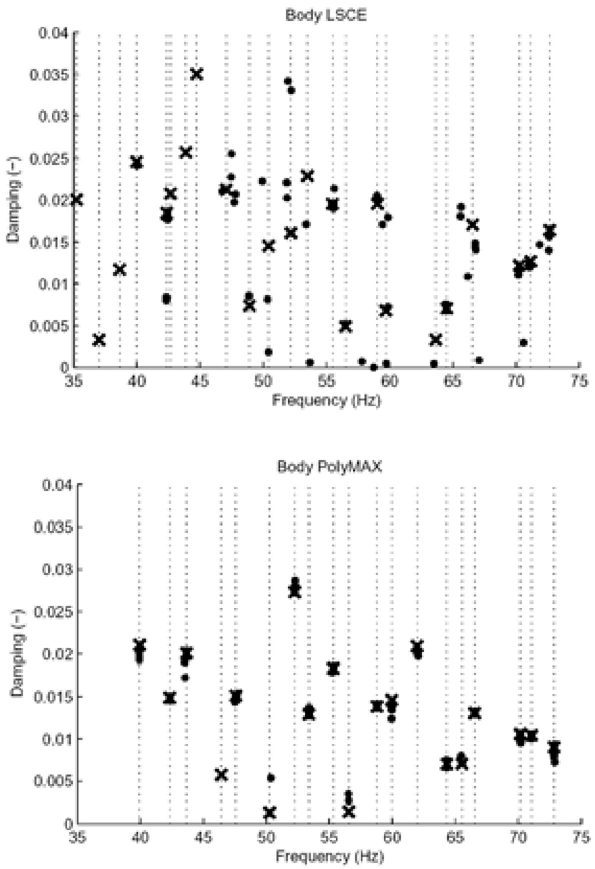


Figure 4. Body LSCE (top) and PolyMAX (bottom) pole selection, frequency versus damping

showing clear poles – and only clear poles – throughout the whole frequency band. This resulted in large differences in the number of poles selected by the different participants. The time taken by each participant to make the assessment was measured, and in general, the LSCE tasks took about twice as long to complete as the PolyMAX tasks. In addition, it was found that the experts spent about twice as much time in the assessment as the novices, who were so overwhelmed by the complexity of the LSCE diagrams that they quickly gave up.

Figure 3 shows a frequency spectrum of the pole selection of all the test participants on the two stabilization diagrams. Users 1–4 are the novices, and users 5–8 are the experts. The vertical dotted lines show the selection made by the AMPS tool.
The LSCE diagram (Figure 3 top) clearly shows that the novices encountered difficulties in the 45–60Hz band; not only did they miss poles, there was also a wide variation in those that were selected. Even the experts did not find it easy in this frequency range, as the poles they selected did not line up well, indicating differences in the frequencies. Above 65 Hz, the experts agreed quite well, but the novices missed some of the poles completely. In the PolyMAX diagram (Figure 3 bottom), the majority selected all poles. All users (experts and novices) agree much better, as indicated by the nicely aligned dots.

Figure 4 shows a comparison of the damping of the selected poles. The crosses represent the AMPS selection. A cluster of dots represents consensus over the selection by the different test participants, whereas a scatter over the damping would indicate, in case of novices, lack of experience and feeling for physical damping values. In general the participants demonstrated more consensus with respect to damping in the PolyMAX diagram (Figure 4 bottom) than in the LSCE diagram (Figure 4 top). AMPS largely agrees with this consensus. The sparse number of selections on the 45–60Hz band, explains the differences. There is a remarkable improvement for both novices and experts in that band in the PolyMAX plot.

More details about the benchmark can be found in [7,8]

It is clear that the association of LMS Test.Lab PolyMAX method and AMPS generate user-independent result and can be an educational tool for both novices and experts.

Productivity - How to speed up the iterative process of poles selection on stabilization diagram

The amount of pole information that can be provided in stabilization diagram is in fact bounded by the ability of human mind to interpret them visually. Automatic procedures do not suffer from this constraint and so the pole classification can be based on more extensive information. With AMPS, more poles are selected in just a few seconds and the pole selection procedure can be sped up by using larger band and higher model order size.

The following example shows how LMS Test.Lab PolyMAX and

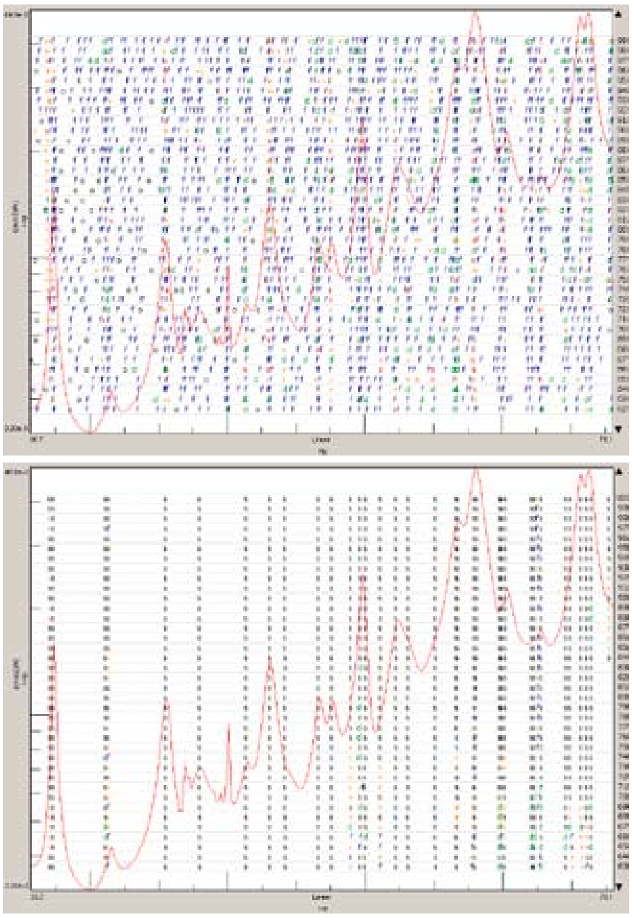


Figure 5. Stabilization diagram of LSCE (top) solver and PolyMAX (bottom) method for a body in white

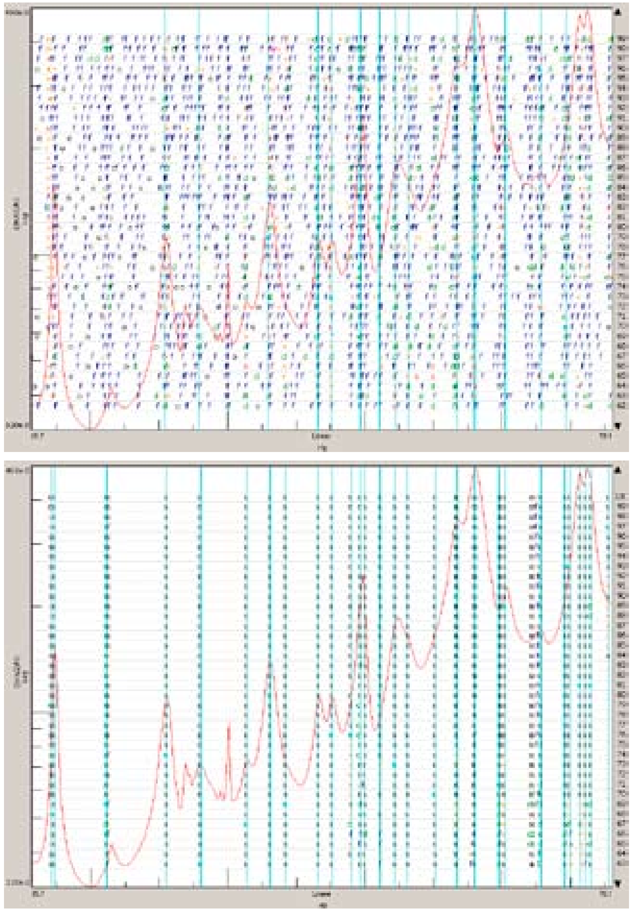


Figure 6. Stabilization diagram of LSCE (top) method and of LMS PolyMAX (bottom) method with automatic modal pole selection (AMPS) for a body in white

the new Automatic modal poles selection (AMPS) can decrease the time required selecting pole selection in the case of a real life problem.

A body in white of a midsize car was instrumented with 2 inputs and 2005 response DOFs. A complete modal analysis was performed by an expert modal analyst over 2 weeks which resulted in 233 poles being found. The iterative procedure, used in this type of modal analysis cannot be applied to the whole band of interest; different frequency bands are analyzed and the poles estimated from each frequency band are then merged into one analysis. With AMPS, the whole frequency range (with 1437 spectral lines) of interest was treated at the same time with a model size of 256. After 40 seconds, 112 poles were highlighted and automatically selected in the stabilization diagram.

In a more detailed study of the range between 36 Hz and 79 Hz, Figure 5 shows that LMS Test.Lab PolyMAX, provides a much clearer stabilization diagram that the LSCE.

When AMPS is applied to both stabilization diagrams, as shown in Figure 6, only 15 poles were selected in the LSCE stabilization diagram whereas in the LMS Test.Lab PolyMAX stabilization diagram, 28 poles were selected in 5 seconds. Figure 7 illustrates the difference between poles selected by expert analyst and those selected in a LMS Test.Lab PolyMAX stabilization diagram by AMPS. The MAC values of 80 % of the poles are close to 85%.

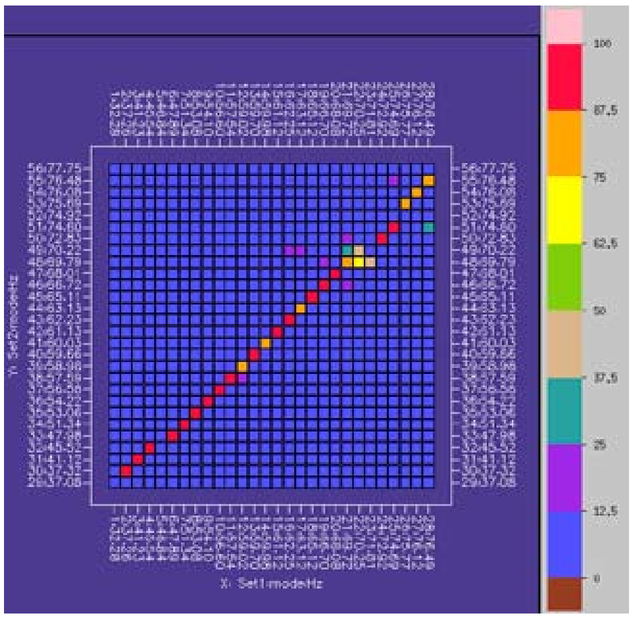


Figure 7. MAC between poles selected by AMPS and poles selected by an expert modal analyst for a body in white

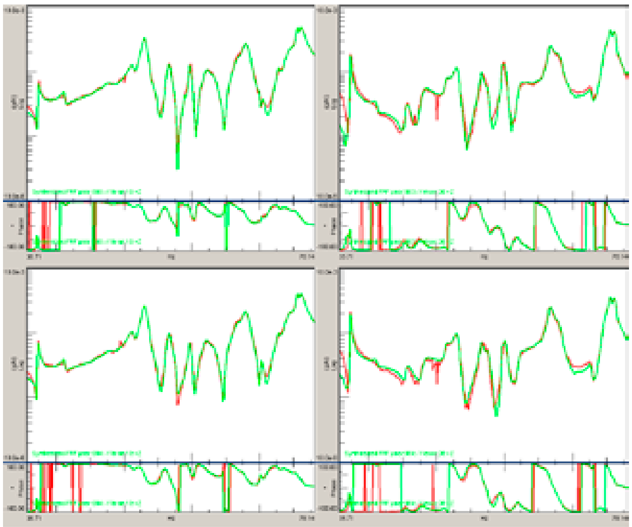


Figure 8. Original (red) and synthesized (green) FRFs of poles selected by AMPS for a body in white

Figure 8 shows the excellent quality of the synthesized FRFs of the modal model generated by the AMPS selection.

Cross-MAC analysis shows very good correlation of most of the modes found by AMPS with those resulting from expert analysis. The estimates of the remaining modes will still need to be refined in an iterative way. For a simple structure, all modes are identified by AMPS, and the time gain achieves a significant 95%. On a more complex structure, where interactive modal analysis is performed on several smaller bands, on average 80 % of the modes are identified with high confidence by AMPS. Taking the remaining interactive analysis time into account, the overall productivity gain still is an impressive 50%.

User-independent results - How to ensure consistent analyses are obtained from different people using the same setup and measurement

The benchmark illustrated well that each individual has his or her own interpretation of the stabilization diagram and as a consequence, experienced modal analysts should perform modal analysis on their own.

As modal analysis is becoming a tool that can be used by both novices and experts, AMPS furnishes the novice with access to expert skills.

AMPS, allows selection criterion to be parameterized, so the same stabilization diagram and the same selection criterion will always provide the same poles selection and automate of modal analysis will be easy.

Analysts: are they still needed?

You may well be asking if it is still essential to have an analyst. It is clear that when analyzing a subframe, for example, there will probably be a very clear stabilization diagram. In this case, the new LMS Automatic Modal Parameter Selection (AMPS) tool reduces the time required for the complete modal analysis procedure. For instance, if there are 20 poles, these must be selected 20 times in stabilization diagram. With AMPS, with only one click on a button, poles will be selected and highlighted automatically in the stabilization diagram, thus really automating modal analysis with predefined band of interest, modal size, and pole selection criterion.

For specific test objects, like a trimmed car, not all modes are excited sufficiently to provide clear and well defined poles in the stabilization diagram. For that kind of databases, AMPS extracts automatically the dominant poles, which proves to be a substantial time gain. The expert's experience then comes in to determine the less dominant poles.

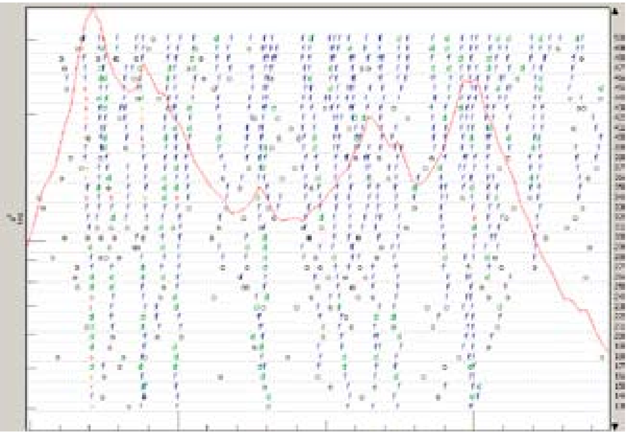


Figure 9. Stabilization diagram obtained by applying balanced realization (BR) to in-flight aircraft data

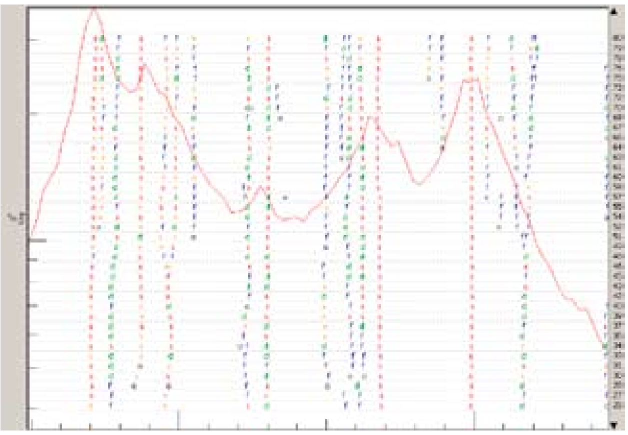


Figure 10. Stabilization diagram obtained by applying LMS Test.Lab PolyMAX to in-flight aircraft data preprocessed to half spectra

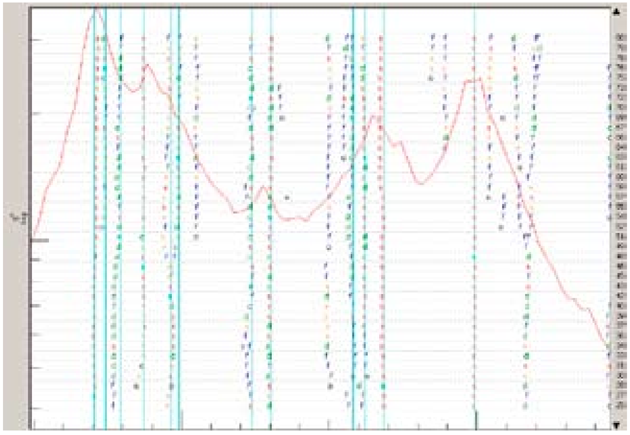


Figure 11. Pole selection with AMPS on a stabilization diagram obtained by applying LMS Test.Lab PolyMAX of in-flight aircraft data

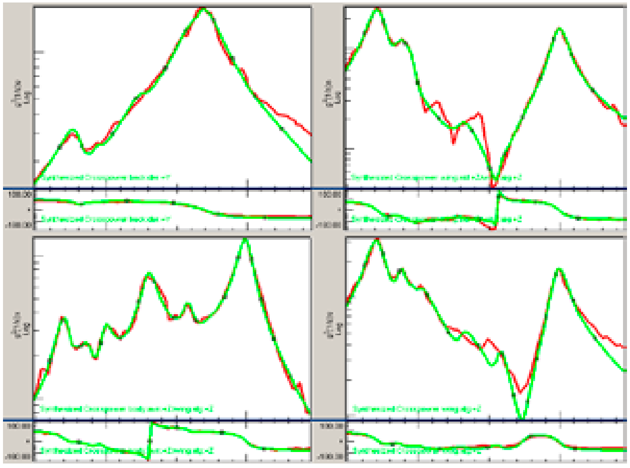


Figure 12. Original (red) and synthesis (green) auto spectra and cross spectra of poles selected by AMPS

Automatic modal parameters selection on aircraft in-flight testing

Operational modal analysis

In the previous paragraph, classical modal analysis cases were discussed. A measured controlled force was applied to the structure in the lab, while the response was simultaneously measured, resulting in an FRF function. However there are multiple situations, where it would be interesting to extract the modal properties from the response data only and this for several reasons. Certain situations can not be reproduced in the lab, such as temperature/mass changes due to operational conditions. For other structures, it might not be possible to either measure the applied force or to excite the structure. It is practically impossible to measure this ambient excitation and the outputs are the only information that can be passed to the system identification algorithm. This situation is described as Operational modal analysis.

At the end of the development cycle, a new aircraft is certified by means of in-flight flutter tests. These tests consist of flying the aircraft at different airspeeds and measuring the accelerations at limited number of locations on the aircraft structure. The aim is to verify that the aircraft does not suffer from aero-elastic instabilities such as flutter. Some of the indicators are the eigenfrequencies and damping ratios with respect to airspeeds. The reason of using modal analysis technique that do not require input information is that it is difficult to measure the force from artificial excitation devices and operational modal analysis also allows the use of natural turbulences as input. However, the analysis of in-flight data poses a number of specific challenges that are related to the complex nature of the test article and the difficulty of the test conditions.

The following case illustrates the use of an output only data set, from an in-flight test of a business jet to obtain data-based dynamic model. During the measurements, no artificial excitation was applied, the excitement was due by atmospheric turbulence, which cannot be measured, but which was assumed to be white noise. Output data was pre-processed into output spectra [10], that are used to identify modal model. The data has 3 reference points and 7 outputs from various points all over the airplane, leading to 21 spectra. Figure 9 shows a typical stochastic subspace identification – balanced realization in this case - stabilization diagram. Figure 10 shows a typical LMS Test.Lab PolyMAX stabilization diagram. It is obvious that it is much easier to identify poles from the stabilization diagram obtained from LMS Test.Lab PolyMAX.

Figure 11 shows poles selected by the new LMS Test.Lab automatic modal parameter selection (AMPS) tool. Figure 12 compares some typical measured half and cross spectra with the spectra that are synthesized from the modal model identified by AMPS. The good correspondence indicates that all the major dynamic properties have been extracted from the data.

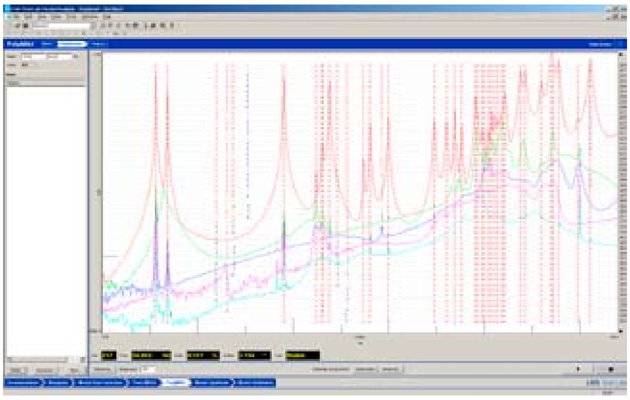


Figure 13. Stabilization diagram of LMS Test.Lab PolyMAX on a satellite

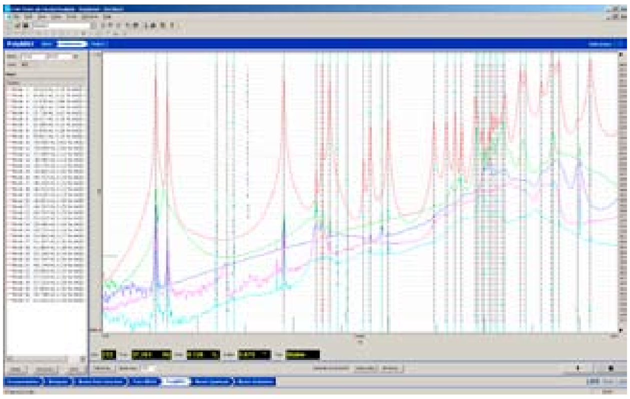


Figure 14. Poles selected by AMPS on a stabilization diagram of LMS Test.Lab PolyMAX on a satellite

Automatic modal parameters selection on satellite

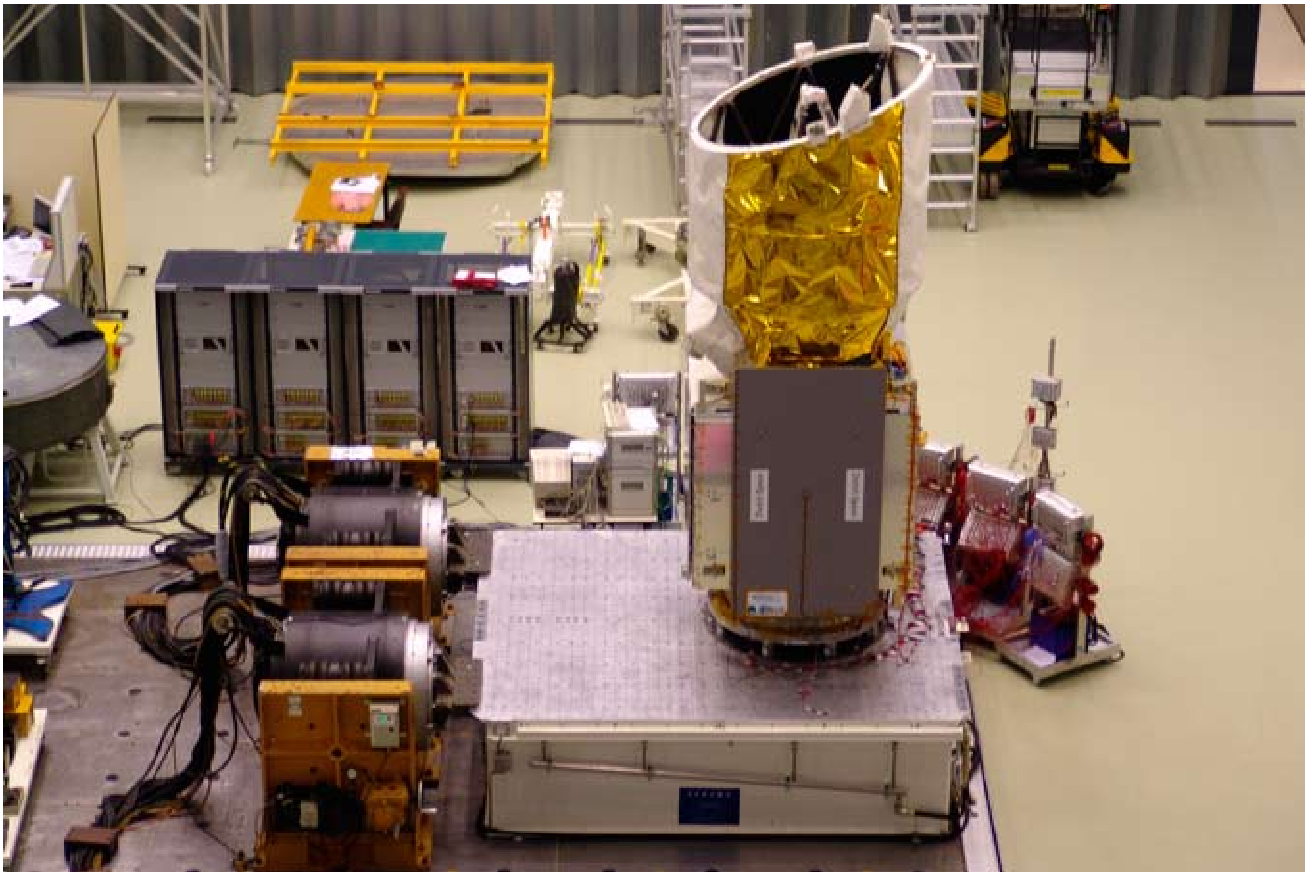
A modal survey test was executed on a very lightly damped structure; a satellite, that was excited with 5 shakers, and measured with 240 degrees of freedom.

The complete frequency range of interest was analyzed at one time, and once again the stabilization is very clear; despite the high modal density at the higher frequencies, LMS Test.Lab PolyMAX is able to separate all of them. It can be seen from the sum of all measured FRF's. (Figure 13, red curve) that the peaks are very sharp, indicating very low damping values, such as would be expected on satellites. With AMPS (Figure 14), the very close poles at the higher frequencies are selected, as an expert should do.

Conclusion

The LMS Test.Lab PolyMAX method and the new Test.Lab Automatic Modal Parameter Selection (AMPS) mean that the myth of automating modal analysis is close to becoming a reality.

The new Test.Lab Automatic Modal Parameter Selection (AMPS) tool improves the productivity by decreasing time consumed by the iterative pole selection procedure. Moreover, this rule-based method, which is unaffected by the ability of a human mind to treat information, results in higher accuracy of pole selection and reduces the uncertainty of the user by the repeatability of pole selection with the same selection criterion. This tool provides valuable guidance for both inexperienced and



experienced users. Consistency between estimates of different analysts can be guaranteed by AMPS tool by applying the same selection criterion on the same stabilization diagram,
The examples cited in this paper prove once again, that this tool meets the needs of real life applications.

The new Test.Lab Automatic Modal Parameter Selection (AMPS) tool opens up a new perspective towards fully automated modal-based applications such as flight qualification of aircraft, structural damage detection, structural health monitoring and improved multi-patch modal analysis.

References

[1] H. Van der Auweraer, C. Liefooghe, K. Wyckaert and J. Debille. "Comparative study of excitation and parameter estimation techniques on a fully equipped car," Proc. of the IMAC 11, the international Modal Analysis Conference, Kissimmee (FL), USA, February 1993.

[2] W. Heylen, S. Lammens and P. Sas. Modal Analysis Theory and Testing. Department of Mecanical Engineering, Katholike Universiteit Leuven, Leuven, Belgium, 1995

[3] LMS International. The LMS Theory and Background Book, Leuven, Belgium, 2000

[4] D. Brown, R.J. Allemang, R. Zimmerman amd M. Mergeay. Parameter estimation techniques for modal analysis. Society of Automative Engineers, Paper No. 790221, 1979

[5] P. Guillaume, P. Verboven, S. VanLanduit, H. Van der Auweraer and B. Peeteers. "A poly-reference implementation of the least-squares complex frequency-domain estimator," Proc. of the IMAC 21, the international Modal Analysis Conference, Kissimmee (FL), USA, February 2003.

[6] B. Peeteers, P. Guillaume, H. Van der Auweraer, B. Cauberghe, P. Verboven, and J. Leuridan. "Automative and aerospace applications of LMS PolyMAX modal parameter estimation method," Proc. of the IMAC 22, the international Modal Analysis Conference, Dearborn (MI), USA, January 2004.

[7] J. Lanslots, B. Rodiers and B. Peeters, "Automated Pole-selection: Proof-of-Concept & Validation," Proc. of the ISMA 2004, International Conference on Noise and Vibration Engineering, Leuven, Belgium, September 2004.

[8] H. Herman Van der Auweraer, B. Peeters, "Discriminating Physical Poles from Mathematical Poles in High Order Systems: Use and automation of the stabilization diagram," Proc. of the IMTC 2004, the 21th IEEE Instrumentation and Measurement Technology Conf., Como, Italy, pages 2193-2198, 2004

[9] LMS International. LMS PolyMAX: A revolution in Modal Parameter Estimation, Belgium, 2004

[10] B. Peeters And H. Van der auweraer:, "PolyMAX: a revolution in Operational Modal Analysis," Proceedings of IOMAC, the 1st International Operational Modal Analysis Conference, Copenhagen, Denmark, 26-27 April 2005.