INDUSTRIAL SOLUTIONS FOR IN-FLIGHT & OFFLINE EXPERIMENTAL FLUTTER ANALYSIS.

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Abstract. Airplane design is currently characterized by front-loading engineering problems to the early stages of the design process, using a range of different simulation tools. Once a prototype is ready, a first flight will take place where aerodynamic and aeroelastic behaviour as predicted by simulation models needs to be confirmed. One such aeroelastic phenomenon is flutter. The overall testing time can be greatly reduced by using smart and dedicated tools that are fit for industrial purposes.

This paper focusses on industrial solutions for experimental flutter analysis. Such a solution needs to be able to acquire data in operational conditions, to automatically perform modal analysis, to make a statement on the actual flutter conditions, and finally, to deal with some sort of flutter prediction. An overview of prediction techniques is given.

The new developments for in-flight data analysis will be illustrated by a simulator-generated in-flight test.

1 INTRODUCTION

Airplane design is currently characterized by front-loading engineering problems to the early stages of the design process, using a range of different simulation tools. However, once a prototype plane is ready, experimental testing can not be by-passed: first there will be ground vibration tests (GVT) to confirm and update the virtual model. After that, a first flight will take place where aerodynamic and aeroelastic behaviour as predicted by simulation models needs to be confirmed.

One such aeroelastic phenomenon is flutter, which is a self-excited vibration of a structure under the influence of a combination of operational forces and aeroelasticity. Although experimental testing takes time, the overall testing time can be greatly reduced by using smart and dedicated tools that are fit for industrial purposes.

Experimental flutter analysis has been around for quite some time now. A nice overview can be found in [1], where both the history of flutter incidents and the history of flutter testing can be found. A first recorded flutter incident is reported on a biplane bomber in 1916, and a first formal flutter test is reported to be carried out as early as 1935 in Germany.

Since then, the approach has always been more or less the same:

1. the airplane flies a number of predefined flight points at different speeds and altitudes at increasing dynamic pressure

2. the airplane is excited using either natural or artificial excitation
3. response signals are acquired from various points
4. data analysis to determine stability: frequency & damping values are extracted
5. the trend of stability is predicted at dynamic pressure higher then measured

To apply this approach in in-flight testing, there is a need for a number of different technologies. First, data needs to be acquired in a reliable way in an operational environment which is not very friendly compared to laboratory conditions. This is usually done by in-flight data recorders and a telemetry system that sends its data to a ground station for analysis. Next, there is the challenge to extract modal parameters from such an operational dataset where the total energy that is exciting the structure is unknown. Finally, there is the need to apply some kind of prediction on the trend of the stability.

The application in an industrial environment requires that this procedure should be fast, reliable, and accurate. While the plane is flying, the determination of stability should not take long as flight time is costly and, moreover, the plane could be in a potentially dangerous condition

This paper describes first the extraction of modal parameters from operational data. Next, an overview of a number of flutter prediction techniques is presented. Finally, an application case is described based on the analysis as suggested by the authors.

2 MODAL ANALYSIS ON IN-FLIGHT DATA

Modal analysis is the estimation of modal parameters as resonance frequencies, damping ratio's and mode shapes. Traditional modal model identification methods and procedures are based on forced excitation laboratory tests during which Frequency Response Functions (FRFs) are measured. However, the real loading conditions to which a structure is subjected often differs considerably from those used in laboratory testing. Since all real-world systems are to a certain extent non-linear, the models obtained under real loading will be linearized for much more representative working points. Additionally, environmental influences on system behavior (such as aeroelastic interaction) will be taken into account.

The challenge involved in modal analysis on in-flight data is that the total energy that is inserted into the system is unknown. The analysis technique to deal with this missing information is generally known as operational modal analysis. Already quite settled in industries such as automotive, it is still slowly introduced in aerospace.

2.1 Operational modal analysis

An accepted way of dealing with operational analysis in industry is based on a peak-picking technique applied to the auto-and crosspowers of the operational responses. Such processing results in the so-called "Running Mode Analysis". By selecting the peaks in the spectra, approximate estimates for the resonance frequencies and operational deflection shapes can be obtained. This auto-and crosspower peak-picking method requires considerable engineering skill to select the peaks which correspond to system resonances. In addition, no information about the damping of the modes is obtained and the operational deflections shapes may differ significantly from the real mode shapes in case of closely spaced modes. Pre-knowledge of a modal model derived from FRF measurements in the lab is often indispensable to successfully perform a conventional operational (running modes) analysis [2].

Therefore curve-fitting techniques, which allow modal parameters to be extracted directly from the operational data, would be of great use for the engineer. Such techniques would identify the dominant modes excited under operational conditions and this information might even be used to improve some traditional FRF tests in the laboratory [2].

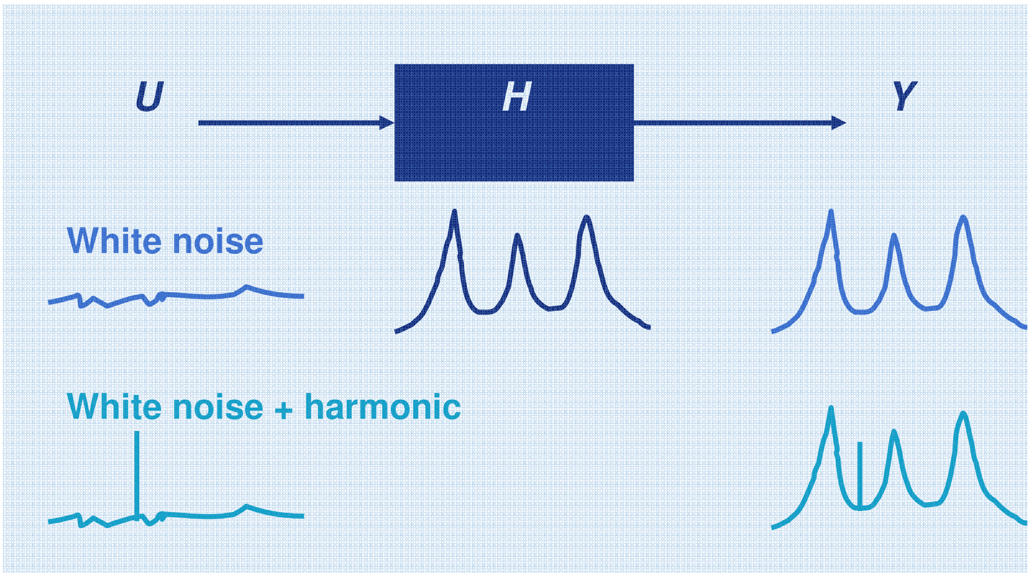

Figure 1: System identification on output-only data.

Figure 1 summarizes the theory of the task to be carried out. The system H needs to be identified using only the output Y. When assuming the input U is white noise, intuitively, having only the output information should be sufficient to identify the system (in terms of modal parameters). If the white noise assumption is not satisfied, e.g. we have a harmonic excitation next to the broadband white noise part, this harmonic will be identified as a mode in OMA. However, in general, it has very low damping and it can be discarded afterwards.

Techniques that can deal with these output-only data include time-domain parameter estimators (LSCE) [3], as well as subspace techniques such as Balanced Realization (BR) [4]. Also, the state-of-the-art discrete LSCF variant called PolyMAX [5][6] for output-only data is available [7][8]. In general, it can be said estimated dampings will not be the same for each of these techniques, but that these more advanced and recent parameter estimation techniques such as PolyMAX, when compared to earlier methods such as BR, reduce the uncertainty on the damping estimates.

2.2 Excitation techniques

From previous flutter incidents [1] it was learned that an inadequate structural excitation will fail to detect flutter and lead to crashes. When the airplane is not well-excited over the frequency range of interest, parameter estimation techniques will not detect the modes correctly. Therefore, a well-known practice in in-flight testing is artificial excitation, in addition to its natural excitation. The benefit of doing so is that the all critical modes are well excited, and that non-linearities in the model are still included.

The excitation technique is always a trade-off between frequency range of interest, weight and power requirements. Different excitation techniques that are commonly used include control surface input (induced by the pilot), rotating wing-tip vanes, pyrotechnics. Some prototype planes have built-in systems to excite the plane through its control surface with sine sweeps over defined frequency ranges, or excitation with random (white) noise.

3 FLUTTER PREDICTION TECHNIQUES

The ultimate goal of flutter testing is to identify instabilities at a very early stage, in any case before it becomes dangerous and/or damaging. Therefore much effort has been put into place to develop techniques to do so. An overview is given, by no means complete.

The decay method uses the decay rate of the response signals as a stability parameter. The longer the decay rate, the closer the system is to flutter onset. This method actually uses the envelope of the impulse response function, and uses extrapolation to predict the flutter onset speed [9].

The damping method is the classical method of flutter prediction [1]. It tracks the damping as an evolution of increasing dynamic pressure. A zero damping is considered as the point where the system becomes unstable and flutter occurs. Based on extrapolation of previously measured flight points, it can be predicted if flutter occurs at the next flight condition. Main difficulty with this method is the choice of the order of the extrapolation. One could conclude flutter onset with a 2nd order polynomial extrapolation, and at the same time a safe and stable condition could be concluded based on a 3rd order polynomial extrapolation.

Zimmerman *et. al.* [10] propose a flutter stability parameter based on analysis of 2 modes. In flutter conditions it is often observed that the system becomes unstable when 2 modes are coupling, where the damping of one of them goes up, and the damping of the other one goes down to zero. So the analysis is based on a 2-degree-of-freedom system. This technique starts with the equations of motion to finally define a flutter stability equation F that can be evaluated with the frequencies and dampings (or decays rates) of the 2 considered modes of the system, for a given dynamic pressure q. This dynamic pressure q depends on the altitude and the speed of the airplane. Next, a curve-fit of these points can be made that describes F as a second-order polynomial function of the dynamic pressure q. This function can be evaluated for $F=0$, which is the flutter boundary. Disadvantage of this technique is that it only calculates flutter onset of 2 modes, therefore multiple combinations have to be tracked. Next to that, if flutter onset occurs which is not due to coupling of modes, the flutter onset speed cannot be predicted correctly.

Other techniques include the method introduced by Nissim and Gilyard [11], the flutterometer method [12], and techniques based on simplified linear aeroelastic models [13].

4 APPLICATION CASE

Industrial application of flutter testing asks for systems that are able to acquire data in operational conditions, to automatically perform modal analysis, to make a statement on the actual flutter conditions, and finally, to deal with some sort of flutter prediction. LMS provides the combination of a data acquisition platform fit for in-flight testing (Scadas frontend family) as well as software tools to analyze this data online.

Such a software tool needs to be able to handle output-only data, which is Test.Lab Operational Modal Analysis (OMA), with a powerful parameter estimator, which is Operational PolyMAX. Finally, it needs to be able to automatically extract the modal parameters, which is done by the Automatic Modal Parameter Selection tool AMPS[14]. Such techniques become increasingly reliable when applied on clean stabilization diagrams such as the ones yielded by PolyMAX.

The combination of OMA, PolyMAX, and AMPS, makes it possible to perform flight flutter testing is an industrial application. The following application case discusses the analysis results of this industrial application, that consists of a simulated flight flutter dataset on a wing from ONERA.

4.1 ONERA Flight Simulator

A Flutter Simulator developed at ONERA allows to generate signals representative of accelerometers measurements recorded during a plane flight test. The global architecture of the simulator is composed of a real time calculator coupled with an analog output device. Basically, the operating of the simulator is very simple, only two parameters are needed as inputs: the altitude and the speed (or Mach number) of the flight. Once flight conditions have been fixed, an aeroelastic model allows the calculation of temporal signals and thus the generation of these “simulated sensors responses”.

The principle is based on the data of a wind tunnel model presenting an aeroelastic instability observed during real wind tunnel tests in transonic conditions. The concerned type of flutter was the classical phenomena due to the coupling between the two first structural modes of a wing (bending and torsion) [15]. In order to perform numerical simulations, reduced models of the structural and aerodynamic behaviours are built. The structural part consists on the results of a ground vibration test limited to the first six symmetrical structural vibration modes. The aerodynamic part is derived from the calculation of the generalised aeroelastic forces (GAF) calculated with the well known Doublet Lattice Method [16]. A state-space model of the GAF [17] is introduced in the classical equation of the fluid-structure coupled system. The resolution of the differential equations system allows to obtain the generalised coordinates as function of time and therefore the time histories of accelerations. Assumptions have been performed to obtain structural responses very similar to those observed on a real airplane when the pilot imposes an impulsion on the command of a wing aileron.

The presented database was carried out for a Mach number of 0.8 and the altitude was varied within the range [8000;4000] m. For each couple (Mach, Altitude), LMS Test.Lab software combined with the LMS SCADAS III data acquisition hardware was used to record four analog signals generated with the ONERA Flutter Simulator.

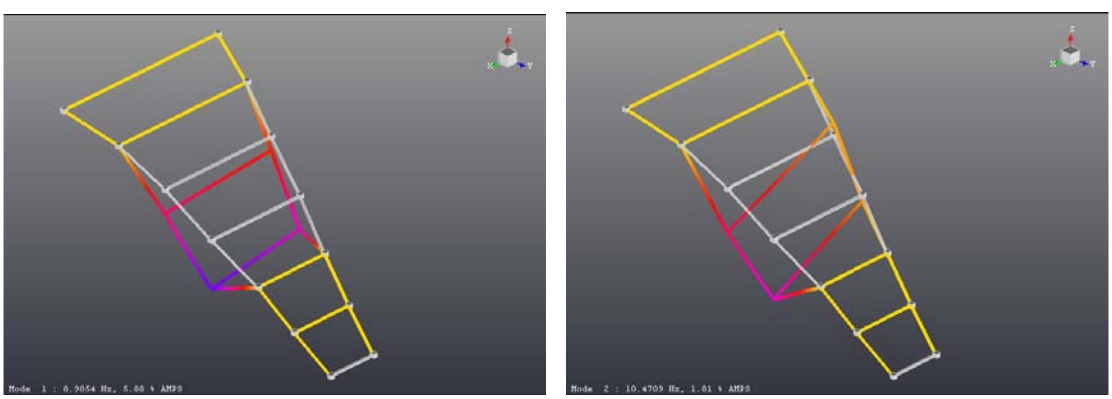

Figure 2: Wing aileron model, with first bending mode (left) and first torsional mode (right).

This resulted in 4 responses on a wing aileron model, see Figure 2, for decreasing altitudes of 8000m, 7000m, 6500m, 5500m, 5000m, 4500m, and 4000m. The theoretical flutter onset occurs at 3870m. Figure 3 shows the very clean stabilization diagram for the 8000m response signal with the modes automatically selected, while Figure 2 shows the model deformations for the first bending mode and the first torsional modes. It is these 2 modes that actually couple at 3870m.

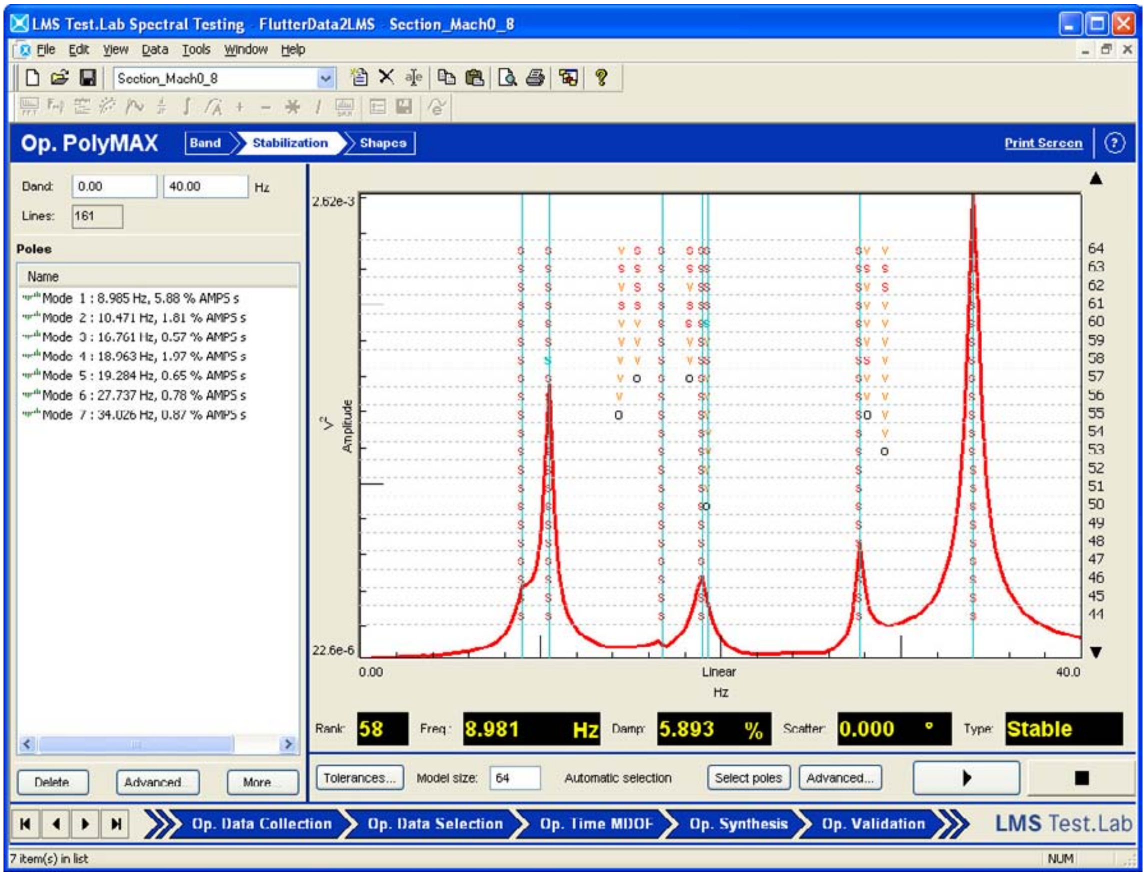

Figure 3: Stabilization diagram with automatically selected poles at 8000m altitude.

For the data set that is closest to the flutter onset speed and altitude, which is measured at 4000m, the stabilization diagram looks very problematic, with almost only 1 visible mode, as can be seen in Figure 4 (left). The deformation of the torsional mode shows that the bending and torsional modes have coupled, see Figure 4 (right). They have shifted to each other in frequency (9.78Hz vs. 10.06Hz), with the damping of the first one going up to 12%, and the damping of the second one going down to 0.16%: flutter!

Figure 5 shows how the 2 modes are coupling as an evolution of altitude. While the altitude decreases, at constant MACH number 0.8, the dynamic pressure increases, and the frequencies of the 2 modes are moving closer to each other, while their dampings diverge.

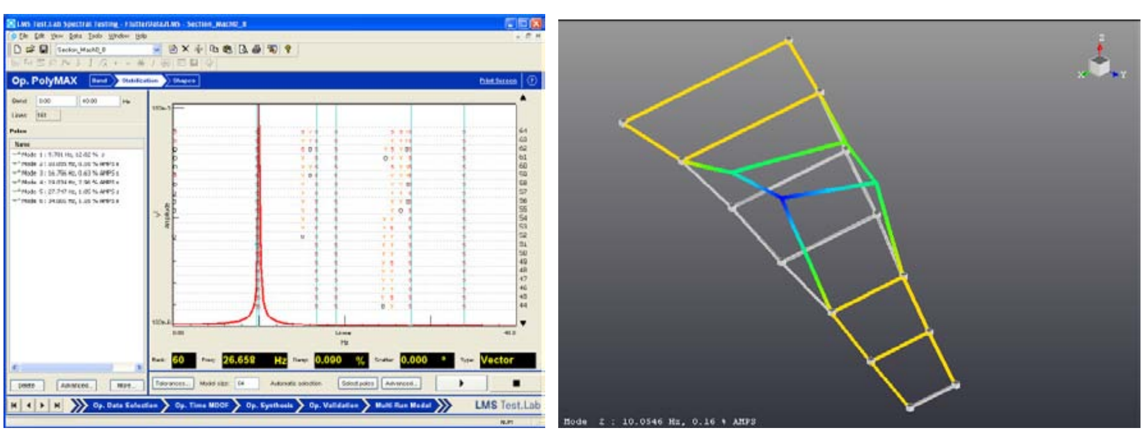

Figure 4: High amplitude of the first torsional mode, and visible coupling of the first bending and torsional modes.

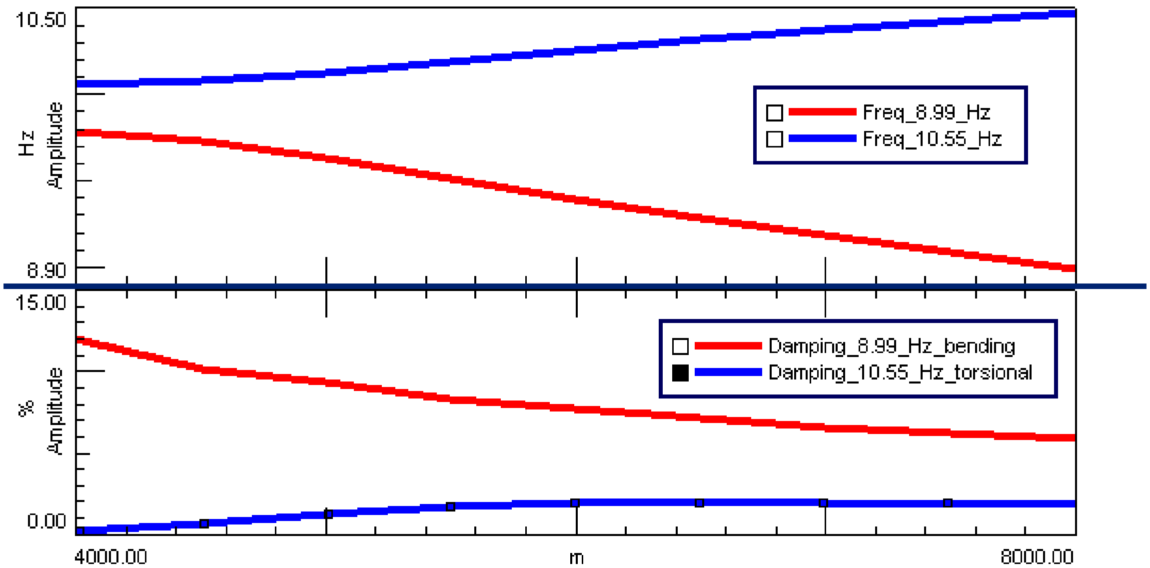

Figure 5: coupling of first bending (red) and first torsional mode (blue), viewed as evolution of altitude.

These results were cross-checked with the analytical model that acted as input for the simulator. Figure 6 shows these results, where the analytical data is represented by the straight line, and the extracted modes from Test.Lab Operational Modal Analysis are represented in squares. All modes were extracted automatically with the deterministic AMPS tool [14].

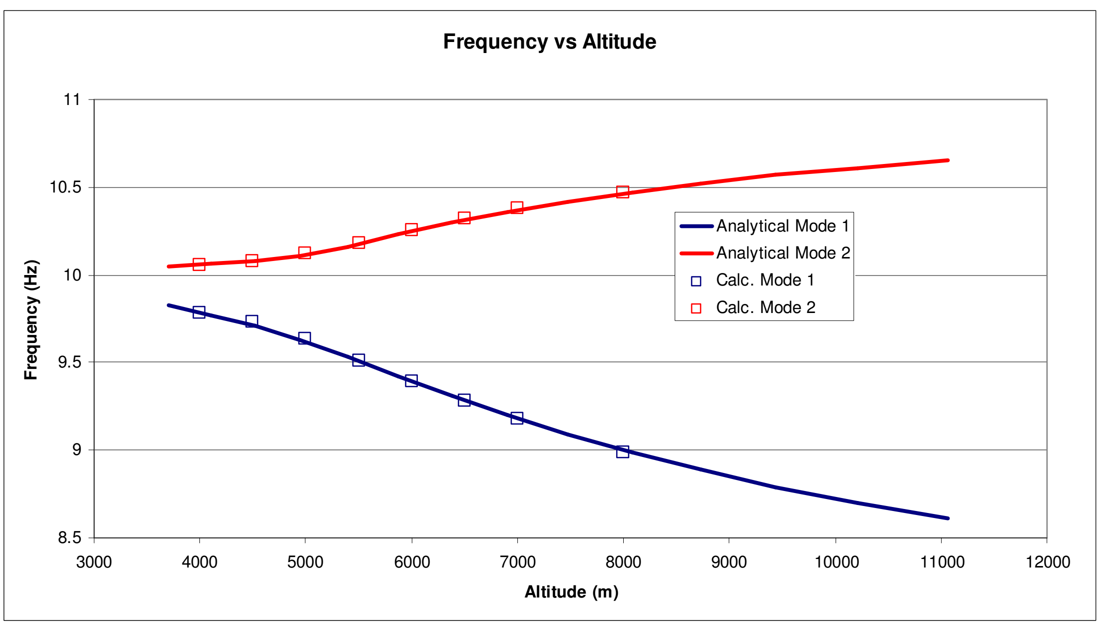

Figure 6: OMA extracted frequency data plotted in squares on top of the analytical model. The top curve is the evolution of the first bending mode, the bottom one is the torsional mode.

The squares follow both curves nicely, not only in the flight conditions that are stable, but especially also in the flight conditions that are unstable and at flutter onset. For the damping, a similar curve was found, see Figure 7. Also here we can see that the damping values are extracted nicely according to the analytical model.

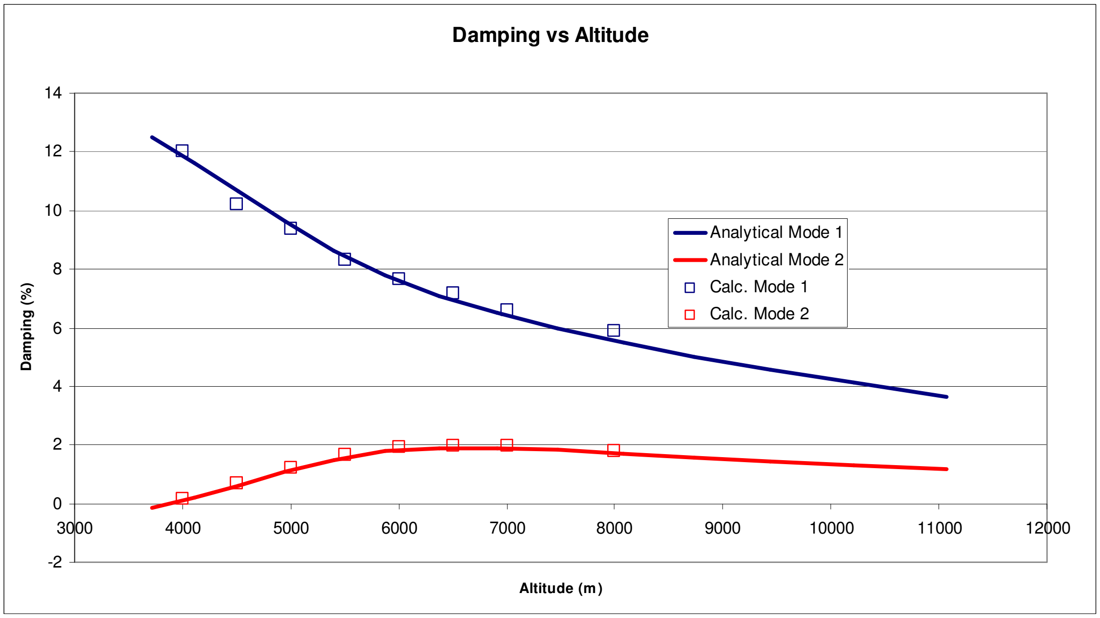

Figure 7: OMA extracted damping data plotted in squares on top of the analytical model. The bottom curve is the evolution of the first bending mode, the top one is the torsional mode.

Finally, the last step of Operational Modal Analysis is to compare the synthesis of the crosspowers with the measured crosspowers. Figure 8 shows the synthesis of the crosspower and synthesis for 2 flight points. On the left, one can see the flight point at 8000m, on the right the flight point at 4000m. It can be clearly seen that the 2 modes in the left display have coupled to one mode with high amplitude at an altitude close to flutter onset on the right. Next, it can be observed that the synthesis and measured crosspower are matching very well.

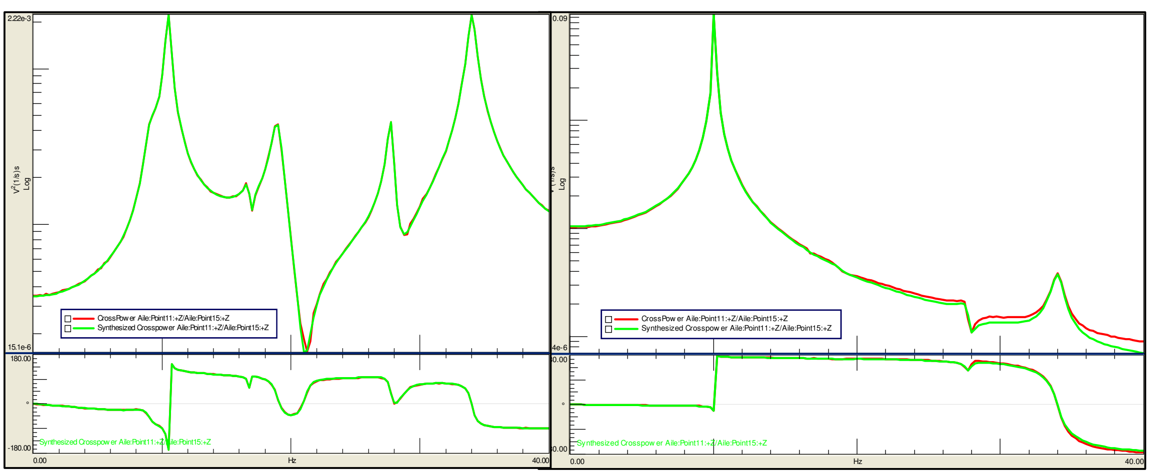

Figure 8: Synthesis of crosspowers for flight point 8000m (left) and 4000m (right).

5 CONCLUSION

A method was presented to combine 3 tools: Operational Modal Analysis, PolyMAX parameter estimator, and AMPS automatic modal parameter selection. It was shown that these state-of-the-art industrial tools are fit for the purpose of flutter onset detection. It was shown that PolyMAX & AMPS correctly estimates the damping values of the system, which is also reflected in the fit of the synthesis of the crosspowers. Validation was done with the analytical values for the frequencies and damping values that were used to create the flutter simulator data. It was also shown that using output-only data is sufficient to execute this task.

Further research should focus on validating this result with real in-flight flutter data. Such data is not readily available, first due to confidentiality, and second also mainly due to absence of real flutter onset in such datasets.

6 REFERENCES

[1] Kehoe, M.W. (1995). *A Historical Overview of Flight Flutter Testing*. AGARD Conference Proceedings 566, Advanced Aeroservoelastic Testing and Data Analysis.

[2] LMS International (2009). Operational Modal Analysis. *Test.Lab 9B Theory Document*.

[3] Hermans L., Van der Auweraer H. (1997). "On the Use of Auto-and Cross-correlation functions to extract modal parameters from output-only data, *Proc. of the 6th International conference on Recent Advances in Structural Dynamics*.

[4] Basseville, M., Benveniste, A., Goursat, M., Hermans, L., Mevel, L., and Van Der Auweraer, H. (2001). Output/only Subspace-Based Structural Identification: From Theory to Industrial Testing Practice, *In ASME J. of Dyn. Systems, Meas. And Control*, 123(4).

[5] Guillaume, P., Verboven, P., Vanlanduit, S., Van der Auweraer, H., and Peeters, B. A poly-reference implementation of the least-squares complex frequency-domain estimator. *Proc. of IMAC 21, the Int. Modal Analysis Conf., Kissimmee, FL, USA*, 2003.

[6] Peeters, B., Guillaume, P., Van der Auweraer, H., Cauberghe, B., Verboven, P., and Leuridan, J. (2004). Automotive and aerospace applications of the polymax modal parameter estimation method. *Proc. of IMAC 22, the Int. Modal Analysis Conf.,* Dearborn, MI, USA..

[7] Peeters, B., Vecchio, A., and Van der Auweraer, H. (2004). PolyMAX modal parameter estimation from operational data. *In Proceedings of the ISMA 2004 International Conference on Noise and Vibration Engineering*, Leuven, Belgium.

[8] Peeters, B., Van der Auweraer, H., Vanhollebeke, F., Guillaume, P. (2007). Operational modal analysis for estimating the dynamic properties of a stadium structure during a football game. *Shock and Vibration – Special Issue: Assembly Structures under Crowd Dynamic Excitation*, 14(4):283-303.

[9] J. E. Cooper, P. R. Emmett, J. R. Wright, and M. J. Schofield. (1993). Envelope function - a tool for analyzing flutter data. *Journal of Aircraft*, 30(5):785–790.

[10] Zimmerman, N.H. and J.T. Weissenberger (1964). Prediction of Flutter Onset Speed Based on Flight Flutter Testing at Subcritical Speeds. *Journal of Aircraft*. 1(4): p. 190-202.

[11] E. Nissim and Glenn B. Gilyard. Method for experimental determination of flutter speed by parameter identification. (1989). NASA Technical Memorandum 2923, NASA, Dryden Flight Research Center, Edwards, CA, USA..

[12] R. Lind and M. Brenner. Flutterometer: An on-line tool to predict robust flutter margins. (2000). *Journal of Aicraft*, 37(6):1105–1112.

[13] De Troyer, T., Zouari, R., Guillaume P., and Mevel, L. (2008). A new frequency-domain flutter speed prediction algorithm using a simplified linear aeroelastic model. In *Proceedings of the International Conference on Noise and Vibration Engineering ISMA*, Leuven, Belgium.

[14] Lanslots, J., Rodiers, B., Peeters, B. (2004). Automated Pole-Selection: Proof-of-Concept & Validation. *Proceedings of the International Conference on Noise and Vibration Engineering ISMA*, Leuven, Belgium.

[15] Viguier, P. (2003), Wind tunnel test of a non-linear flutter model, *International Forum on Aeroelasticity and Structural Dynamics*, Amsterdam, Netherlands, 4-6 June 2003.

[16] Albano E. and Roden, W.P., (1969). A Doublet-Lattice method for calculating lift distribution on oscillating surfaces in subsonic flows. *AIAA Journal* Vol.7 n° 2 1969 pp 279-285.

[17] Tiffany, S. H. and Karpel, M. (1989), Aeroservoelastic modeling and approximations of the unsteady aerodynamics. NASA Technical Memorandum 101574, April 1989.