DIGITAL INDUSTRIES SOFTWARE

Aircraft ground vibration testing

Enhancing the efficiency of aircraft structural dynamics testing

Executive summary

Ground vibration testing (GVT) is a major milestone in the aircraft certification process. The main purpose of the test is to obtain experimental vibration data for the entire aircraft structure so you can validate and improve its structural dynamic models. Among other things, these models are used to predict flutter behavior and plan safety critical flight tests. GVT is typically performed late in the development cycle, and due to the limited availability of the aircraft, there is pressure to get the test results as quickly as possible. Simcenter™ software and hardware solutions contain a number of technological advancements that help engineers perform GVT more efficiently without compromising the accuracy of the results.

SIEMENS

Abstract

Increasing complexity in modern aircraft systems and structures makes it more and more challenging for engineers to develop aircraft within time and budget constraints. Aircraft structural design must be carefully verified to meet performance requirements but also guarantee safety. On one hand, stringent regulations for reduced emissions call for more lightweight structures such as composite materials and innovative aircraft architectures, which creates lots of uncertainty around structural dynamic performance. On the other hand, new urban air mobility concepts enabled by electric propulsion offer possibilities for disruptive vertical take-off and landing (VTOL) aircraft configurations. This calls for more engineering work to validate and tune the performance of such innovative designs.

Most of the verification tasks performed during the aircraft development cycle are driven by the certification process. Testing is used as one of the methods to prove compliance with certification requirements and verify the accuracy of predictive simulation models. GVT fits in this process. This large-scale modal test typically happens at the integrated aircraft level, right before the first flight, and is conducted to fulfill specific requirements as requested by the certification authorities. These requirements are linked to the aircraft type and size. For normal, utility, aerobatic and commuter aircraft, the certification specification CS23.629[1] defines the critical flutter requirements that prove the aircraft is free from flutter, control reversal and divergence for any condition of operation within the flight envelope. Similar requirements apply to larger aircraft that are subject to CS25.629 certification specification. In the corresponding advisory circular document, ground vibration testing is explicitly listed as an acceptable means of compliance for proving aircraft is free from flutter. GVT is required for new aircraft development programs, but also in the case of major structural modifications to an existing program, or in the case of new store configurations for military aircraft.

The goal of GVT is to test/verify program-critical flutter simulation results and reduce the risk of flight flutter tests.[2] More specifically, this large-scale modal test on the full aircraft serves to calibrate computer-based finite element (FE) models used for further flutter predictions. The results of the test are the modal parameters of the aircraft structure and include modal frequencies, damping values, mode shapes and scaling factors for a number of configurations. During the GVT campaign, structural coupling tests involving the flight control system are also performed to help calibrate the simulation models and control laws. These calibrated aero-servoelastic models are then used for flutter predictions to analyze the behavior of the aircraft throughout its flight envelope and reduce the risk of the flight flutter test.

Ground vibration tests are typically performed late in the development cycle, once the fully integrated aircraft is ready. And due to the limited availability of the aircraft and the fact that multiple configurations need to be tested, extreme time pressure exists to get the test executed as quickly as possible. Anything that can speed up this process is a great advantage for the aircraft program. It is essential for the test teams to have the right tools and process in place to efficiently perform all stages of the test campaign from test preparation and test execution to analysis and reporting of the results. Simcenter embeds a number of innovative solutions that allow you to drastically reduce the time of each step in this process without compromising the accuracy of the results. Thanks to an integrated end-to-end process, the aircraft digital twin can be thoroughly validated and the design cycle can be accelerated.

Ground vibration testing: modal test on the full aircraft structure as part of the certification process.

Covering the full process

Test teams need to go through a managed process to accelerate the test campaign at all stages. First of all, test preparation as well as the post-test analysis and correlation with prediction models can be greatly accelerated with an integrated use of FE models. The test can be performed more efficiently by using a flexible and accurate data acquisition system and properly choosing the excitation techniques. This helps to focus on the most critical phenomena and make the best use of limited testing time. On-the-spot analysis of the test data also helps to make decisions on whether to move to the next test configuration. Finally, once the test is done, a tremendous amount of data needs to be handed over to the analysis team. This should be transferred in a smart way so the data is easily accessible and can be quickly processed and provide the desired results. Let's look at each of these steps and see how innovative techniques help to streamline and accelerate this process.

Test preparation and the integrated use of FE models

Finite element analysis (FEA) is a standard technique for modeling the dynamics of complex structures. The goal of the GVT is to extract modal information from the physical aircraft to improve the fidelity of these models. But conducting a modal test on such a large and complex structure can be a difficult task with many questions to be answered. For instance:

How many accelerometers should be used?

Where should they be placed on the structure?

Where to attach the shakers to properly excite all targeted modes?

Is the suspension soft enough to ensure the first flexible mode is well separated from the rigid body modes?

Although not updated yet, the FE model available prior to the GVT can provide precious information on the aircraft dynamic behavior to optimize the test setup and duration. Pretest simulations make use of the preliminary FE model to answer the above questions. For instance, on a light structure such as an unmanned aerial vehicle (UAV), the mass loading effect from the sensors and cables might be significant. Sensitivity analysis can be performed upfront using the FE model to minimize these effects during the test. Similarly, the number of exciters and their locations can be efficiently studied virtually to optimize the test.

Simcenter 3D software provides all the tools to efficiently perform these pretest investigations. The minimum modal assurance criteria (MAC) sensor selection algorithm, for instance, is provided to automatically select the best sensor locations from a set of candidate measurement points. The selection is based on the optimization of the auto modal assurance criteria matrix and ensures that each mode of vibration is uniquely identified during the modal test. Pretest planning can also optimize the number and location of exciters to ensure that all target modes are adequately excited during the test. The test geometry is then automatically generated in the FE environment and is ready to be transferred to the test team to efficiently instrument the aircraft. Additional exported data such as reduced mode shapes and synthetized frequency response functions can also be useful for real-time correlation of the results during the test.

With such integrated use of FE models before the test, the communication between test and simulation teams improves. It allows them to start working together as a team, using pretest to define and validate the test setup. This helps to create buy-in from both ends and will ensure efficient collaboration right from the start of the test campaign.

Using dedicated hardware and software to efficiently verify the test setup

Instrumenting an aircraft for a GVT can be a tedious task. Hundreds of sensors are typically required to properly capture the vibration of the structure. Each sensor must be attached at a precise location and with the required orientation. With such a large number of sensors, errors can easily be made leading to erroneous results and delayed test campaigns. Using an efficient technique to validate the setup is essential to accelerate the process. Based on Siemens' decades of experience in the field of structural dynamics testing, Simcenter SCADAS hardware and Simcenter Testlab™ software efficiently guide the test engineer through the instrumentation and setup verification to start the measurement task as quickly as possible and with full confidence.

The Simcenter Testlab instrumentation app, for instance, can be of great help. Running on a tablet or any mobile device, it allows the engineer to freely move around the structure and check the instrumentation. The application remotely connects to Simcenter Testlab running on the central computer to define the sensor parameters such as the sensor serial number, attachment location or orientation on the aircraft structure. It also allows you to document the test setup in detail by automatically associating pictures of the sensors to the corresponding channel data in the measurement project. Transducer electronic data sheets (TEDS) technology is also useful for automatically defining the sensor parameters in the measurement project. Serial number and sensor sensitivity are automatically read from the sensor chip, which helps avoid manual errors.

Not only the sensors but also the complete measurement chain must be carefully checked before starting tests. Analog sensors are connected to data acquisition frames for signal conditioning and analog-to-digital conversion. Given the high number of sensors distributed on the large aircraft structure, total cable length for connecting sensors to data acquisition frames can be massive and often leads to measurement issues. Distributing the acquisition frames around the structure to minimize cable length can be a great asset. This is easily done with the Simcenter SCADAS. The data acquisition frames can be distributed around the aircraft and placed closer to the sensors – for instance, underneath each wing. The systems are daisy-chained using fiberoptic cable and operate as a single monobloc system with perfect synchronization between channels.

This makes the data acquisition system scalable and easy to adjust to the test requirements and desired number of measurement channels.

During GVT, the aircraft is typically lifted from the ground with a soft suspension system that creates a free-free condition. The goal is to ensure good separation between the rigid body modes and the first flexible mode. Multiple exciters are also required to properly excite the aircraft structure and obtain high-quality modal data.

Electrodynamic shakers are typically used for aircraft ground vibration testing and are attached to the aircraft structure at the wings, tail and possibly on the fuselage. The Simcenter SCADAS system not only provides measurement capabilities for the input sensors, but also generates output signals for these shaker amplifiers. Injected force is usually measured using a force cell or impedance head at the connection point between the shaker and the aircraft structure. Linear current-controlled amplifiers are also commonly used in GVT. The input voltage to the

Lateral and vertical exciters placed on the aircraft engine during the certification of the A340-600 (images courtesy of Airbus, Onera and DLR).

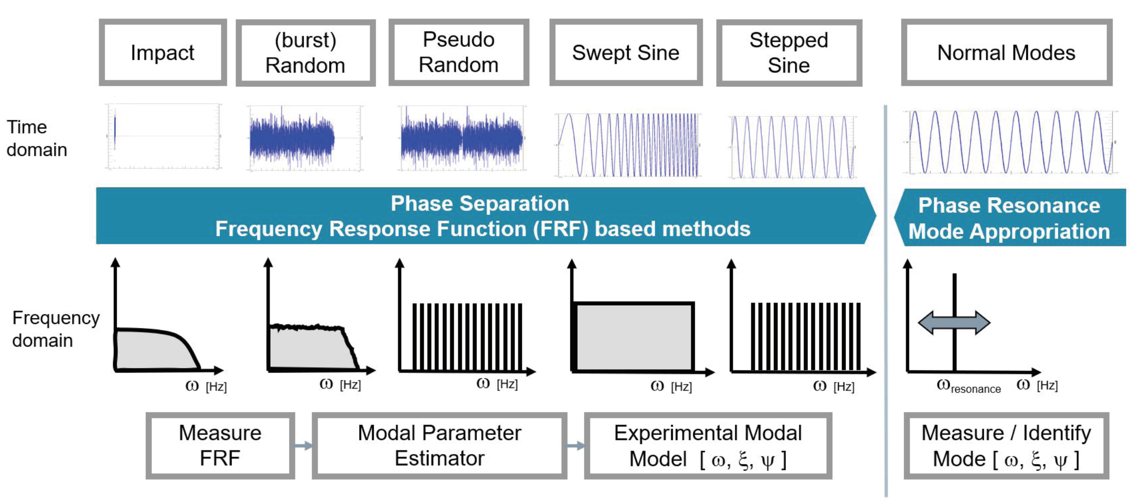
Simcenter SCADAS and Simcenter Testlab for data acquisition and processing.

amplifier is directly proportional to the injected force, which is useful for structural nonlinearity studies. Simcenter SCADAS is ideally suited for large channel count measurement campaigns such as GVT. The system offers high channel density – each frame can host up to 480 acquisition channels and can be daisy-chained with other frames. It also features low-frequency AC filter at 0.05 hertz (Hz), which is an important requirement to accurately capture low-frequency resonant modes on very large structures. When using Integrated Electronics Piezo-Electric (ICP) sensors, the system also automatically reports incorrectly connected sensors or faulty cables, which drastically helps troubleshooting the test setup. Principal component analysis of the response signals is also a powerful tool to troubleshoot the exciter part of the setup, especially when many shakers are attached to the structure. Rigid body properties (center of gravity, moment and product of inertia and rigid body modes) can also be verified during the GVT by processing the vibration data as part of the setup validation.

Full range of excitation signals for accelerated measurements

Once the setup has been validated, the challenge for the test team is to perform the measurement as quickly as possible while making sure all-important phenomena are captured. The excitation signals used during a GVT are mixed and can include impact, random, sine and normal mode excitation. Properly selecting the excitation signal during the measurement campaign allows the user to greatly accelerate the measurement task. A first assessment can be performed on the aircraft structure by doing a simple impact test. Burst random or pseudo-random – based on multi-sine signal – have the advantage of exciting the structure on a broad frequency range and thus to capture many resonant modes in a rather short measurement time. Sinusoidal excitations such as swept or stepped sine have the advantage of focusing the energy in one spectral line at a time, reaching higher excitation levels. Although more time-consuming, it can be particularly interesting to perform nonlinearity assessments while exciting the structure with different load levels.[3] All these excitation signals – from impact to stepped sine – are grouped under phase separation methods. Using this technique, frequency response functions (FRFs) are calculated and further processed to extract modal parameters.

The phase resonance method, also called the modal appropriation technique, is used in the context of GVT, especially for the modes that are critical for flutter predictions. This method consists of tuning the excitation so the deflection shape matches a particular mode shape and makes the structure vibrate as a purely real mode. When properly tuned on a specific mode, the method gives a snapshot of the mode and does not need any mathematical algorithm for postprocessing. The goal is thus to focus on one mode at a time, which is more time-consuming but provides highly accurate results. As it is using a different methodology to extract the modal parameters, this method also helps you gain confidence the test results will meet aircraft certification requirements.



Using complementary excitation techniques during a GVT to accelerate the measurement process.

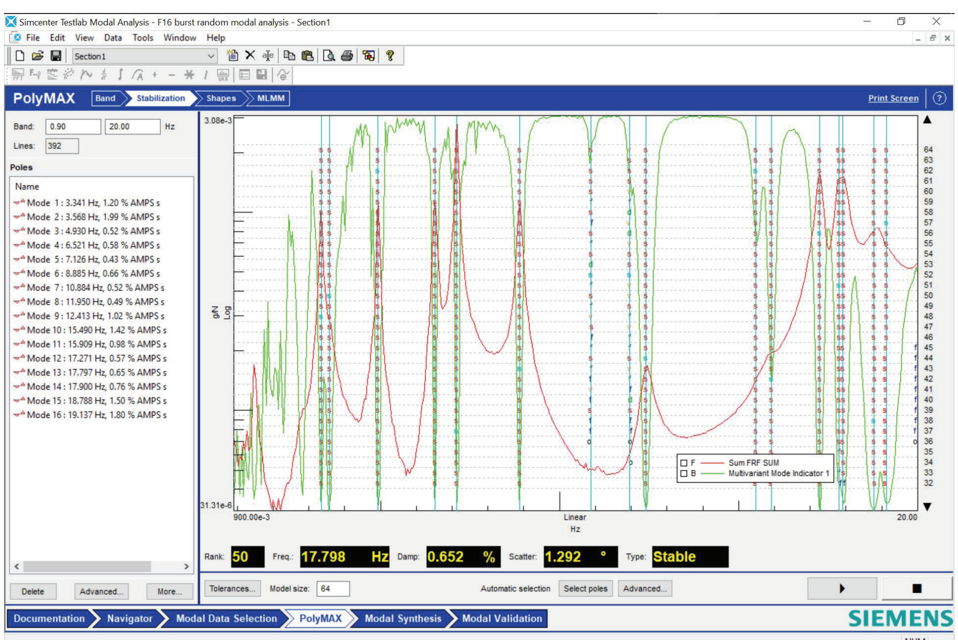
In stepped sine and normal modes testing, a control algorithm continuously maintains the prescribed amplitude and phase as defined in the setup for each control response. If these deviate outside the bounds, then an update to the system transfer matrix is done automatically online to readjust the output to the amplifier to bring the levels to the reference. This makes it possible to investigate nonlinearities in the structure by accurately measuring the vibration response of the aircraft structure for various excitation levels.

As a summary, different excitation techniques are often used during a GVT and this is important because the test duration for each methodology is quite different. If the GVT is done using only the normal modes technique, it will take a lot of time. So, a mix of excitation techniques is preferably used to speed up the process. The duration of the GVT campaign can consume from a few days to a couple of weeks, depending on the size of the airframe, the number of channels and the number of different payload or mission configurations to be tested. It is important to test any airplane configuration that can have an effect on flutter performance. If it is determined that structural responses can change significantly due to additional payload or fuel configurations, then a GVT must be performed on that configuration. Recent GVT campaigns have shown the testing time can be significantly reduced by using the right combination of excitation signals.[4]

Swift data processing and modal parameter estimation

The next step in the process is the analysis of the acquired data and extraction of the modal parameters. Based on the frequency response functions collected using the phase separation method (impact, random or sine excitation), the general modal model is calculated using a curve-fitting parameter estimator. Simcenter Testlab Modal Analysis features the state-of-the-art and patented Polymax algorithm,[5] which allows you to simplify this process and make accurate assessments of the data immediately after the test. The Polymax method allows the user to analyze a large frequency band containing a large number of modes and provide clear stabilization diagrams, making it easy to select the poles of the modal model. This helps to get user-independent results and higher-quality modes in a short time, which is an important asset in the context of aircraft certification. Once the poles have been selected, the resonant frequencies, mode shapes and modal damping values are readily available to be analyzed and compared with expected results from simulation.

When using a phase resonance technique (normal modes excitation), the modal data is a direct outcome of the mode tuning. Methods such as force in quadrature, exponential decay or complex power are applied to evaluate both structural damping coefficients and generalized mass values.



Using the Polymax algorithm to obtain clear stabilization diagrams.

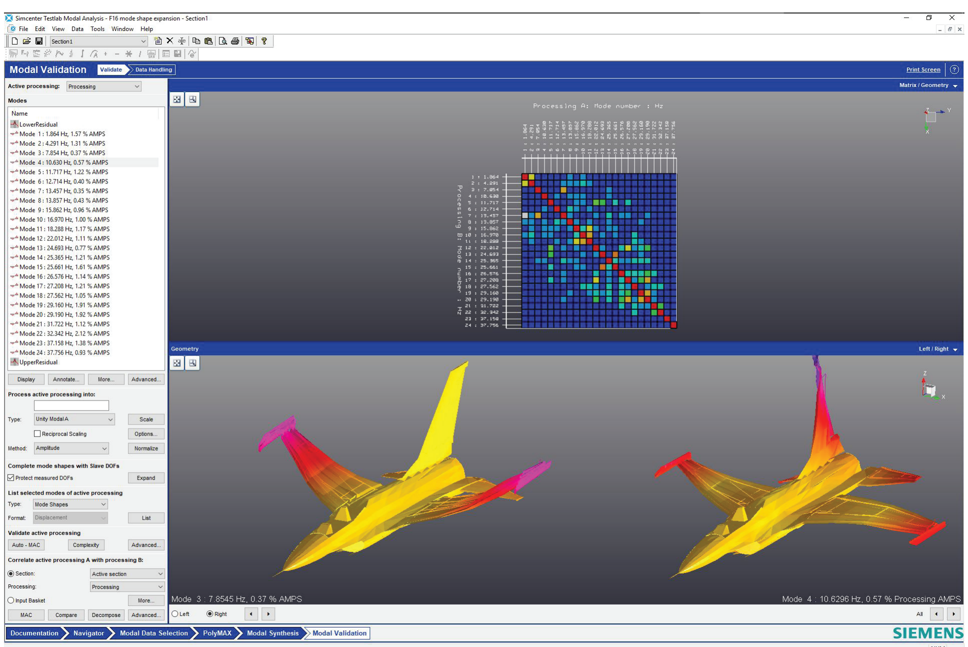
Extensive modal data validation and feedback to analysis teams

During a ground vibration testing campaign, it is important for the test teams to be able to quickly check the validity of the measured data. Simcenter Testlab allows you to efficiently evaluate the quality and analyze the sensitivity of the results within the parameters selected by the user. Comparing FRFs synthesized from the modal model with the physical measured FRFs, for instance, helps to validate the obtained results. Comparing different mode sets based on the modal assurance criteria matrix is also helpful to ensure that modes are properly measured.

As mentioned, the main purpose of GVT is to obtain a modal model that can be compared with the FE model and update the FE model appropriately. A typical constraint is to have modes that are real and reciprocal. To impose this constraint on the test modal model, an extension to the Simcenter Testlab modal analysis is available called maximum likelihood modal model (MLMM).[6] This method automatically iterates on the calculated parameters of the constrained modes to improve the fit to the measured FRFs. The MLMM method brings extra accuracy in terms of resonant frequency and damping estimates and accelerates the processing task when dealing with a higher level of complexity of measured structures. More consistent and user-independent results are obtained, which can then be used with higher confidence during the aircraft verification process, while keeping the existing testing processes unchanged.

Typically, modal parameters extracted from the test data are first evaluated at the test site by comparing the expected results from computer-based finite element predictions. This post-test assessment is done to make sure there are not any blatant differences before the test is disassembled. The modal assurance criterion is a useful indicator to quantify the amount of correlation between a set of test and analysis mode shapes. It enables you to easily compare various modal analysis results and quickly assess the quality of the test data.

Once the ground vibration test is completed, experimental data is handed over to the analysis team for further validation of the aircraft digital twin. If there are discrepancies in the results between test and analysis, then the FE model goes through an iteration process to update the model and bring it in line with the test results. Sensitivity analysis can be performed to get insight into the parameters of the FE model, which should be modified to improve the correlation with the test data. Once a validated FE model is obtained then it can be used for analysis, which continues with flutter predictions.



Assessing the quality of the modal results based on mode shapes and the MAC matrix.

Full data traceability and test reporting

Because the ground vibration tests serve the certification process of the aircraft, it is important to ensure the entire test campaign is properly documented, and that all data is fully traceable. Simcenter Testlab allows you to store all important testing parameters such as sensor serial numbers and sensitivity, tested configurations and measurement parameters in a consistent way and in a central location. All raw and processed data is consistently stored and clearly organized for easy post-test verification. Test reports are also automatically generated, allowing the user to share engineering insights using active pictures. The final test results can be seamlessly transferred to the analysis team using common data models for further processing in the FE packages. These improved traceability and reporting capabilities greatly support the certification process.

Conclusion

Ground vibration tests are used for verification of the aircraft structural models, which result in more accurate flutter predictions. They are an essential milestone in the certification process of the aircraft. The Simcenter hardware and software solutions are designed to cope with the main challenge of today's GVT campaigns; that is, to reduce the testing and analysis time without compromising the accuracy of the results. Highly efficient testing is made possible by integrating complementary excitation techniques in a single software environment. Built-in modal analysis capabilities ensure the test data are validated, and the aircraft modal parameters are available almost in real-time during the test. The integrated use of test and FE models allows optimal planning for GVT and has the advantage that a correlated FE model is available shortly after the test. Embedded reporting capabilities ensure full traceability of the test and serve to efficiently support the certification process.

This combined set of capabilities in the Simcenter testing solution, both on the hardware and software side, is the result of Siemens' more than 30 years of experience in the field of structural dynamics. This solution has proved to be extremely efficient in providing improved accuracy and insights as well as reducing the time needed for a GVT campaign from weeks to days on many recent commercial and military aircraft programs.

References

1. Federal Aviation Administration, Means of Compliance with Title 14 CFR, Part 23, §23.629, Flutter. https://www.faa.gov/documentLibrary/media/Advisory_Circular/AC_25_629-1B.pdf
2. "Airbus uses Simcenter Testlab to improve and streamline its flutter analysis process," Siemens Digital Industries Software, Airbus Flutter case study.
3. Ahlquist, J.R.; Carreño, J.M.; Climent, H.; De Diego, R.; De Alba, J., "Assessment of non-linear structural response in A400M GVT," Structural Dynamics, Volume 3. Conference Proceedings of the Society for Experimental Mechanics Series, New York, 2011.
4. Lubrina, P.; Sinske, J.; Govers, Y.; Lastere, N., "AIRBUS Beluga XL state-of-the-art techniques to perform a Ground Vibration Test campaign of a large aircraft." The International Forum on Aeroelasticity and Structural Dynamics 2019, Savannah, Georgia, USA, IFASD-2019-041.
5. Peeters, B; Van der Auweraer, H; Guillaume, P.; Leuridan, J., "The PolyMAX Frequency-Domain Method: A New Standard for Modal Parameter Estimation?", Shock and Vibration, 11, 395–409, 2004.
6. El-kafafy, M.; Peeters, B.; Guillaume, P.; De Troyer, T., "Constrained maximum likelihood modal parameter identification applied to structural dynamics," Mechanical Systems and Signal Processing. 72-73. 10.1016, 2015.

Siemens Digital Industries Software

Americas: 1 800 498 5351

EMEA: 00 800 70002222

Asia-Pacific: 001 800 03061910

For additional numbers, click here.

About Siemens Digital Industries Software

Siemens Digital Industries Software is driving transformation to enable a digital enterprise where engineering, manufacturing and electronics design meet tomorrow. Xcelerator, the comprehensive and integrated portfolio of software and services from Siemens Digital Industries Software, helps companies of all sizes create and leverage a comprehensive digital twin that provides organizations with new insights, opportunities and levels of automation to drive innovation. For more information on Siemens Digital Industries Software products and services, visit siemens.com/software or follow us on LinkedIn, Twitter, Facebook and Instagram. Siemens Digital Industries Software – Where today meets tomorrow.

siemens.com/software

81896-D4 1/22 A