Advanced GVT Testing of the Gulfstream G650

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Ground vibration testing (GVT), one of the critical tests that occur during aircraft development, is typically one of the last tests to take place prior to embarking on the flight test program, providing valuable information for the validation of the aeroelastic stability of the aircraft. Historically, GVT is required by aviation regulators in the certification process. This highly visible and time-constrained test has evolved over the years as new data collection tools, both hardware and software, have become available. The Gulfstream G650 aircraft serves as an example of how modern approaches have allowed this required test to provide highly evolved information much more efficiently and with improved confidence, dispelling the myth that testing has to be time-consuming, costly, and complicated to be considered successful.

Gulfstream Aerospace Corporation has recently added a new flagship aircraft to its fleet of long-range business aircraft. The G650 is a technologically advanced twin-engine business aircraft with an advanced fly-by-wire flight control system as well as many other significant improvements. It is designed to cruise at speeds of Mach 0.85 to 0.90, with a maximum speed of Mach 0.925 and will have a range of up to 7,000 nautical miles (13,000 km). The aircraft has an overall length of 99 feet, 9 inches (30.40 m), an overall span (wingspan plus winglets) of 99 feet, 7 inches (30.35 m), and a height of 25 feet, 8 inches (7.82 m). Figure 1 shows the G650 aircraft; Figure 2 provides a three-view display with dimensions.

A critical test in preparing for the aircraft flight test and certification program is the ground vibration test (GVT), which is used to characterize the dynamic properties of the aircraft in multiple configurations prior to flight test. The objective of the GVT was to measure aircraft responses on the ground to confirm and validate finite-element model predictions. Two primary aircraft configurations were tested: zero wing fuel with stabilizer nose neutral and full wing fuel with stabilizer nose neutral. Overall aircraft dynamic behavior was characterized for these configurations, with further testing completed for aircraft control surfaces and other subsystems. The GVT is a critical-path test, since it occurs shortly before the flight test program begins and helps confirm the finite-element models used to predict aircraft dynamic loads and aerodynamic responses. These models in turn are used to guide the flight test program by predicting the flight stability of the aircraft.

Historically, aircraft GVT can be a time-consuming process.[1,2] Preparing the aircraft, installing instrumentation, and conducting a large number of tests for different aircraft configurations can take a considerable amount of time. Often, new aircraft designs require weeks to complete all testing required to satisfactorily achieve the GVT results; a single change in configuration could require days of testing. Advances in GVT methods over the past 40 years take advantage of improvements in instrumentation and computing hardware as well as enhancements in modal methods. These advances allow a GVT program, like the one performed on the G650, to be completed very efficiently to meet a very compressed time schedule.

Gulfstream teamed with ATA to prepare for and conduct the G650 GVT. With proper test planning, implementation of new modal testing tools, and the ability to work around the clock, the complete GVT program for the G650 was completed in less than four days. Completing the test within this short time provided significant cost savings by freeing the aircraft for other processes in preparation for the flight test program.

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Figure 1. Gulfstream G650 aircraft.

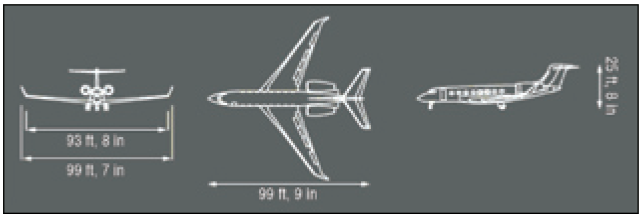

Figure 2. Three-view layout of G650 with dimensions.

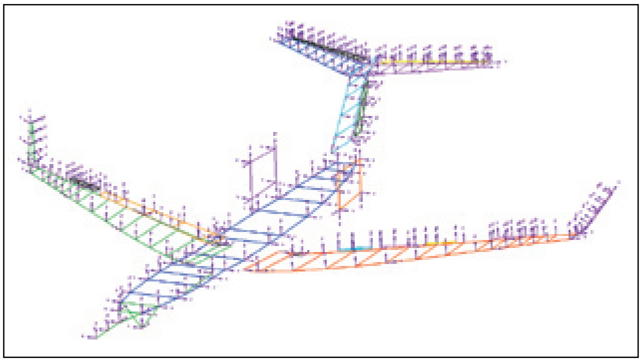

Figure 3. Test display model of the G650; arrows indicate where measurements were made.

Test Preparation Activity

Appropriate test preparation can yield significant rewards in testing efficiency and accuracy of results. These activities are those that can be completed well in advance of the aircraft availability for GVT. The preparation activities can guide the test program and minimize the number of test-time actions required after the aircraft has been committed to the GVT program, thereby reducing the total time when the aircraft is not available for other activities.

The pretest analysis model preparation and evaluation are typically a significant test preparation activity. In collaboration between test and analysis engineers, the finite-element model can be used to effectively select appropriate accelerometer measurement locations as well as locations where excitation of the aircraft should be applied. Further, the finite-element model can be used to develop a simplified test display model that can be used to evaluate test results as soon as they are available.

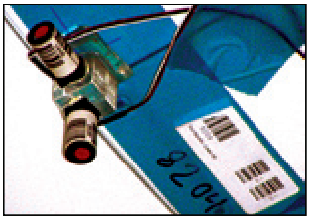

Figure 4. Bar codes placed on sensors and at measurement locations enhance setup.

The test display model allows both test and analysis information to be displayed and compared to assure that all appropriate test data have been acquired during the test program. This approach was used for the G650 program, where Gulfstream provided the aircraft finite-element model (FEM), and ATA developed the corresponding test display model (Figure 3). This test display model shows all of the measurement locations selected for the GVT (392 sensors). It was prepared so that back expansion to the full display model could be performed using all measurement results. Evaluation of the FEM results using the test display model allowed all of the measurement local coordinate systems to be checked well in advance of the test and verified that the model results could be directly compared to the test data.

Using the FEM to prepare for the test allows the quantity of test measurements to be selected with high confidence and verifies that the locations and number required can properly define the modes of interest. Proper selection of the number of measurements allows the data acquisition system to be configured appropriately. Given that, many data acquisition systems today can acquire hundreds, if not thousands, channels of data; this does not generally impose a significant constraint on the test preparation. Nonetheless, it can assist in ensuring that the data acquisition system is properly selected for the job at hand.

At the same time the measurement locations are defined, preparation for the installing the sensors can be made before the aircraft is available. Geometry definition is prepared for each sensor to clearly define where the sensors are to be installed. Measurement tools and templates are also developed, which will speed the test setup process. Once the locations are known, some of the layout for sensor installation can be performed prior to the test, while the aircraft is undergoing other final preparations. Predefining sensor location tags or bar codes that will later be used in automating the sensor hookup can also be accomplished at this early stage.

Table 1. Many aircraft test configurations were defined in planning stage.

Test Series	Targeted Component	Aircraft Fuel Configuration	Hydraulics Configuration
1	Overall aircraft	Empty	All on
1	Overall aircraft	Full	All on
2	SMI rudder	Empty	All on
2	Elevator rotation	Empty	Dual actuation
2	Elevator rotation	Empty	EBHA inactive EHSA active
2	Elevator rotation	Empty	EBHA active EHSA inactive
2	Elevator rotation	Empty	EBHA electric EHSA inactive
2	Aileron rotation	Empty	Dual actuation
2	Aileron rotation	Empty	Right hydraulic off
2	Aileron rotation	Empty	Left hydraulic off
2	Aileron rotation	Empty	Electric mode
2	Elevator hinge line, SMI support	Empty	All on
2	Aileron hinge line, SMI support	Empty	All on
2	Rudder rotation	Empty	Dual actuation
2	Rudder rotation	Empty	Right hydraulic off
2	Rudder rotation	Empty	Left hydraulic off
2	Rudder Rotation	Empty	EBHA active in electric mode
2	Flap, starboard	Empty	All on
2	Rudder hinge line, SMI support	Empty	All on, yaw damper off
2	Rudder hinge line, SMI support	Empty	All on, yaw damper on
2	Rudder hinge line, SMI support	Empty	All on, alt. mode, yaw damper on
3	Wing flutter exciters	Empty	All on
3	Nose boom, impact test	Empty	NA
3	RAT, impact test	Empty	NA

Figure 5. G650 aircraft undergoing GVT.

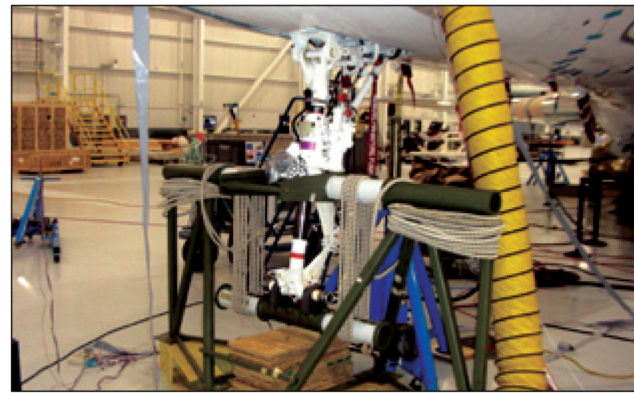

Figure 6. Bungee suspension system installed at nose landing gear.

ATA has implemented a bar-code system where all sensors and measurement locations are identified with a bar code tag, as shown in Figure 4. The system also takes advantage of recent sensor advances that use TEDS identification of sensors through the data acquisition system.[3] This allows accurate, automated sensor installation to be verified all the way through to the data collection hardware. A significant amount of measurement setup data entry can be performed before the test setup, so that the final channel definition is quickly completed as the sensors are installed.

A complete set of test configurations was defined for the GVT to validate the dynamic behavior of the aircraft. The first series of tests focused on identifying the overall airframe modes in the empty- and full-fuel configurations. This was followed by a significant number of control surface tests in the second series. These included multiple flight control and hydraulic system configurations. Also included were structural mechanical interaction (SMI) tests where the control surfaces were used to excite the aircraft while evaluating the aircraft behavior.

Collecting these test data helped develop a better characterization of the flight control system in preparation for subsequent test programs, showing added value in the GVT. A third series of tests was conducted to focus on specific components of the aircraft, including the nose boom and the ram air turbine (RAT). Table 1 summarizes the tests conducted during the course of the GVT. Note that most of these tests were conducted using multiple excitation types and levels to characterize the linearity of the aircraft as well. Gulfstream and ATA selected the sequence of tests based on priority of the information to be obtained as well as the most efficient order to complete the tests. With the pretest analysis, test sequence definition, and instrumentation layout completed, the GVT was started once the aircraft was available.

Implementing New Methods

After thorough pretest preparation for the GVT, further steps were implemented to allow the GVT to be completed as efficiently as possible. The aircraft was prepared for the GVT and installed on a soft suspension while the aircraft instrumentation was being installed. Figure 5 shows the aircraft in the hangar test area. The suspension system, designed and built by Gulfstream, used a series of bungee loops installed with special support hardware at the landing gear. The nose gear suspension is shown in Figure 6. This bungee suspension provides a simple, effective isolation system that can be easily adjusted for varying load conditions.

ATA provided the data acquisition system used for the GVT so that all data channels could be acquired simultaneously. This system incorporated VXI hardware with Brüel &Kjær Test for I-DEAS software. This allowed multiple tests to be conducted quickly, without requiring any data collection system channel configuration changes. In addition to the 392 sensor locations defined, six shaker force signals, the shaker command signals, and input location accelerations were also acquired for more than 400 channels.

Separate data collection and data analysis computing systems were provided to allow data to be acquired at the same time that data were being analyzed and compared to finite-element predictions. ATA provided IMAT (MATLAB™-based) software for data processing tasks and for comparison to analysis predictions. In many cases, time-domain data were acquired and stored for post-processing into frequency response functions on another computer system. This parallel processing of data allowed testing to be completed without major interruptions. Further, since MATLAB and IMAT were heavily used, this provided flexibility in how the data could be evaluated. Specially developed tools that might not be available in standard software products allowed quick on-site decisions to be made.

The six shakers for the overall airframe studies were installed at the aircraft wingtips, the horizontal stabilizer tips, and the engine nacelles. This allowed the entire aircraft to be excited using both random and sine excitation while collecting all of the acceleration data. Multiple force levels were applied to study how the behavior of the aircraft changed with varying excitation force. Subsequent sine testing also made use of the shakers installed at these locations.

All of these steps have become a common part of an efficient GVT process being used today. To increase the efficiency of the test program, ATA implemented two new techniques. The first involved an excitation approach called multi-sine.[4] The second involved using a new data analysis tool called AFPoly.[5] Incorporating these methods into the GVT process helped assure that there were no delays either in completing the excitation and data collection process or in the modal parameter extraction process.

Multi-sine is an excitation technique where multiple shakers are used to apply multiple sinusoidal frequencies to the aircraft at the same time. This is somewhat analogous to the typical multiple-shaker, random-excitation approach that is widely used for modal testing today. By using multi-sine, multiple sine sweeps are effectively conducted simultaneously. Since all shakers are used together, as in a multi–shaker random test, there is no need to change the shaker configurations between sweeps, saving time in the overall process.

Figure 7 shows an example of the excitation forces applied to the G650 (time and frequency response) for a combination of symmetric sine sweeps. The three distinct frequencies shown in the spectra indicate the three different sinusoidal components that were applied and swept together. After the completion of the sweep, the time domain data were processed to yield the frequency response functions used in data analysis. The use of sinusoidal excitation allows higher amplitude excitation to be applied at a given frequency. This can result in higher quality frequency response function data, which has better coherence than a corresponding set of multi-shaker random excitation.

With proper configuration, the sine sweep can be conducted in less time than required for the random excitation, which needs more time to allow for sufficient data averaging. In this test program, the sine sweep excitation was performed in about 75% of the time required for random excitation. Improved efficiency in the test approach allowed all of the various test excitation techniques to be used for a thorough characterization of the aircraft.

Due to the significant number of tests to be completed, data processing efficiency was also important. ATA implemented AFPoly as the key modal parameter estimation tool in addition to other methods in widespread use. AFPoly allowed the data sets to be processed quickly once frequency response data were available for a given configuration. Similar to time-domain polyreference,

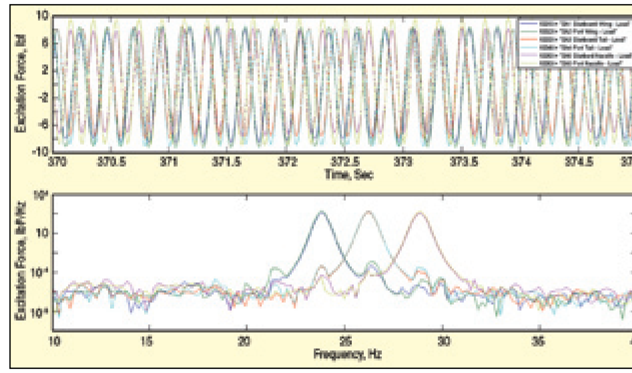

Figure 7. Multi-sine excitation allows for multiple sine sweeps to be conducted simultaneously; excitation forces time domain (top) and spectra (bottom) are shown.

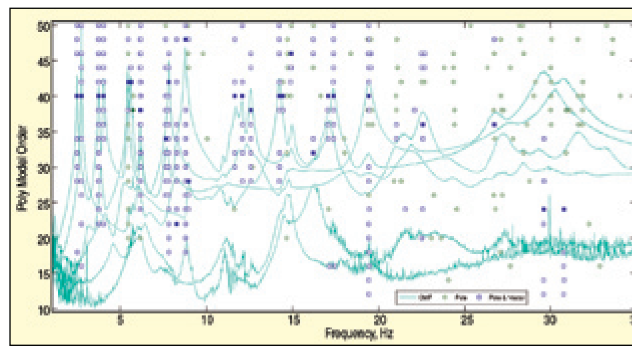

Figure 8. AFPoly stability plot for modal parameter extraction.

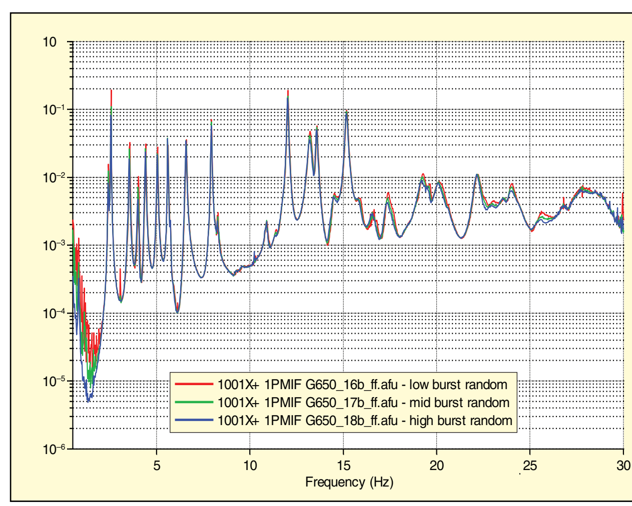

Figure 9. Power mode indicator function used for linearity assessment using multiple excitation levels.

a stability plot is generated using AFPoly, which guides the modal selection process. AFPoly's advantage is that there are fewer indicated computational poles to clutter the stability plot, making the parameter selection process more straightforward. Figure 8 shows a stability plot generated during an estimation process. This method also allows a broader frequency band to be analyzed in a single process, which means that the test results for a given test can be generated more quickly.

Linearity assessments were made as part of the GVT program by conducting data acquisition at a variety of excitation force levels. This testing could be completed quickly and easily, since all data were acquired in a single set. With the data being available for immediate assessment, linearity could be studied without any substantial delay in the testing. Figure 9 shows a mode indicator plot demonstrating the effect of excitation level on frequency content for the overall aircraft. Specific study of the control surfaces showed more characteristic nonlinear behavior as seen in Figure 10, where the elevator response frequencies decrease with increasing force level. These trends were documented for all control surfaces

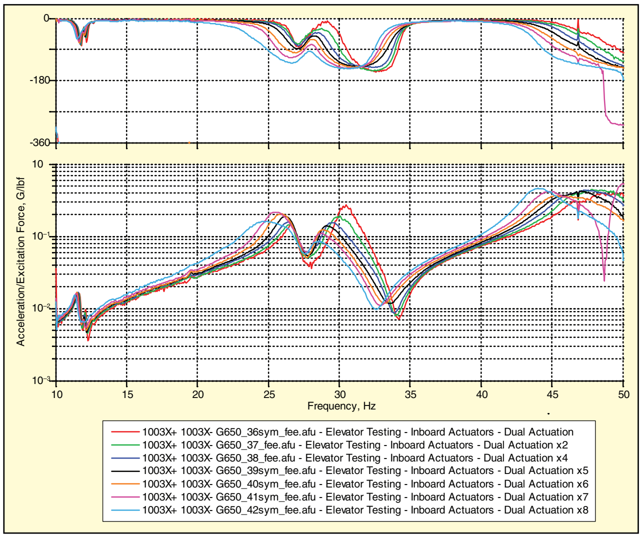

Figure 10. Linearity study of the elevator control surface.

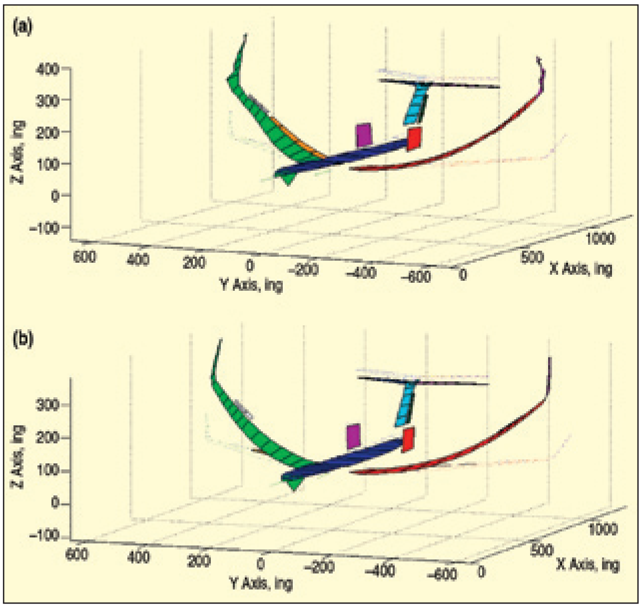

Figure 11. Comparison of test and analysis mode shape results helped test completion decisions.

during the second series of tests.

Having all of the analysis pretest predictions available during the GVT allowed direct frequency comparisons to be generated and mode shape comparisons to be made. Figure 11 shows a comparison of test and analysis shapes, which assisted during the test program. ATA developed a number of specialized tools that allowed the test and analysis shapes to be compared quickly as results became available. These documented which analysis modes had been identified and helped clarify whether further test data were needed.

Recommended Practices

A number of steps were taken to allow the G650 GVT to be conducted as efficiently as possible. As many tasks as possible were completed prior to the aircraft availability to prevent delays once the aircraft was committed to the GVT program. These pretest efforts made sure that all of the instrumentation was properly identified and configured so that final installation could be completed quickly. Substantial channel table configuration was also completed ahead of time to minimize test delays. Use of bar codes and other instrumentation automation features such as TEDS were essential in the setup process. The test display model completed as part of the pretest activity made it possible to check the channel layout and data processing tools prior to the test.

Once the test was started, having a test configuration sequence that was efficiently ordered allowed the test program to be conducted with minimal delays between each test set. Test data acquisition tools were also critical to the process. Use of a data acquisition system that could acquire all data channels simultaneously minimized the total acquisition time required for each test configuration. This allowed multiple data sets to be acquired to study structural variability with excitation level, which was particularly important for control surface studies. The use of multisine excitation helped in this regard, since the total number of sine sweeps required was minimized.

The amount of time required for data processing was also important, since it influenced the assessment of the data acquired in any given configuration. Having the modal parameters extracted in a short time after the data were acquired allowed decisions to be made about whether a given test configuration had been completed. AFPoly was an important tool in this regard. Other useful data analysis and processing tools allowed for comparison between test and analysis results while the testing was being conducted.

Summary

In completing the Gulfstream G650 GVT, a total of 120 unique test runs were performed to complete the full study of the aircraft. This included testing for overall airframe modal behavior in two aircraft fuel states and a large number of control surface tests. The control surface testing also included SMI evaluation, providing valuable assessment of the control system behavior.

To complete such an extensive GVT program in less than four days, an efficient process had to be employed and included implementing new modal testing tools. The evolution of modal testing has reached the point where a large number of sensors can be installed, verified, and measured while applying multiple shaker inputs to the aircraft. Multi-shaker techniques allow a complete characterization of the aircraft to be developed without the large number of shaker moves previously required. Implementing the multi-sine excitation technique allows further improvement by making it possible to conduct a combination of sine sweep tests in significantly less time. Improved data quality could result, since larger excitation forces can be applied.

Modal parameter estimation can be performed using a wide variety of software tools. Any number of these can be used in the data analysis process. Those tools that allow a clear assessment of the modal parameters with fewer data set iterations will permit the modal testing to be completed more efficiently. The use of the AFPoly software for the G650 GVT demonstrated that it could be effective in enhancing the data analysis process, clearing the way for test site decisions.

There are always ways to improve the process of testing so that it does not have to be considered a time-consuming and expensive endeavor. Since the GVT is such a critical test process required in the development of a new aircraft, new tools such as those used in this G650 GVT are essential to the further improvement and efficiency of the modal testing process.

Acknowledgement

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