New Concepts in Aircraft Ground Vibration Testing

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A collaborative demonstration and development test was performed on a 737-200 transport airplane, during October 2003. The objective was to demonstrate, develop, or explore several concepts that offer promise of breakthrough efficiencies in the modal testing of airplanes, or ground vibration testing. Participants from an aircraft manufacturer, a university, and measurement hardware and software vendors conducted the test. Concepts were explored in instrumentation, sensor setup, excitation, and data processing – some of which are laboratory proven but new in application to full-scale airplane testing. Briefly summarized, the results show potential for significant timesaving (over current practice) in situations where test requirements permit.

The project described in this article was devoted to demonstrating new technology and exploring concepts, which, if not new, have not been traditionally applied to ground vibration testing of aircraft. The test was unusual in several respects: It was conducted on a shoestring budget with a borrowed airplane in a borrowed hangar. The participants were from diverse organizations representing a university, an aircraft manufacturer, and several vendors of instrumentation. The data system was provided on loan from the manufacturer using MATLAB® software written by a graduate student at the university. Sensors were prototypes on loan from their manufacturer.

A simple test was envisioned that would identify all airplane modes up to 10 Hz, with minimal nonlinear characterization and with a minimalist sensor set. A diverse group of visitors witnessed various portions of the preparation and testing. All testing needed to be completed within a window of opportunity consisting of 48 hours of actual testing time from rolling into the hangar to rolling out of the hangar. In a triumph of cooperation, all objectives were met within the 48-hour window. By arranging to borrow a 737-200 airplane, with only research objectives, we realized a "low-pressure" opportunity to try new, innovative techniques on a full-scale transport airplane.

The test was started with the following objectives:

- Explore and or demonstrate new concepts in ground vibration testing (GVT) of airplanes, which collectively could lead to a breakthrough in reducing the cost and complexity of aircraft GVT and other types of modal testing.
- Demonstrate these concepts convincingly on a realistic test of a representative commercial transport airplane.
- Gather data necessary for the future development of new approaches and identification tools.

Table 1 outlined the main areas of investigation and provided a basis for discussion and 'brainstorming.' Several concepts showed obvious promise for modal testing of aircraft, while further work is needed in other areas. This article focuses on the areas of instrumentation and excitation. Of particular note are the digital sensors, the minimalist sensor set, and transient excitation. The effort to apply photogrammetry was abandoned due to nontechnical reasons. The study of boundary conditions requires further modeling efforts. The nonlinear identification effort was cut short by time constraints.

The first 19 modes of this airplane were successfully identified in a total of 48 hours of test flow time. Several hours were spent investigating and troubleshooting prototype instrumentation. The 'crew,' while experienced, had never worked together on a modal test. Participants and attendees provided a valuable forum for discussing concepts and ideas. Vendors gained insight into this application and shared visions of possible future improvements.

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Figure 1. Digital sensor system on wireless network; ribbon cables provide digital bus connection to sensors.

Instrumentation Setup

Data Acquisition System, Digital Sensors. All data used for modal analysis were taken with a digital sensor system (DSS)[1,2] Pictured in Figure 1 and outlined in the schematic of Figure 2, this system consisted of a laptop computer running MATLAB acquisition software and a small mainframe module to which digital sensors and digitizing modules (DSIT) were connected by ribbon cables. The system as configured for this test was a 64-channel system. A total of 62 accelerometers were distributed on the airplane (discussed below), and two channels were reserved for force signals during the shaker excitation testing. The entire system was very compact and could have fitted in a carry-on-sized bag.

The DSS box was located on a table behind the right hand

Table 1. Main areas of investigation.

Opportunity for Timesaving	Concepts Investigated
Setup of instrumentation	• Digital sensors reduce cabling, offer wide (24-bit) dynamic range. • TEDS sensors automate calibration entry. • Photogrammetry (or other means?) measures location (and possibly orientation?) of sensors, permitting rapid attachment, accurate positioning. • Minimalist sensor set reduces installation time.
Excitation	• Transient excitation.
Quantify departure from linearity	• Quantify amplitude dependant modal parameters from transient or random response, reducing dependence on sine testing. Data acquired for future work.

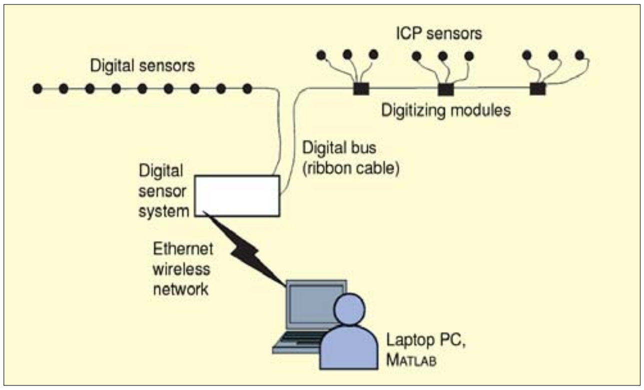

Figure 2. Schematic of digital sensor system; system reduces cabling requirements and features 24-bit sampling.

wing, central to the airplane structure. Five digital bus ribbon cables were routed to sensors toward the vehicle extremities in each direction. This was dictated by a limit of 32 sensors/ cable and a cable length limit of 100 feet (for the cable type available for this test). Clearly, several hours were saved as a result of the reduction in cables (five cables versus 64).

The DSS box included an Ethernet network interface to which was attached a wireless network interface for control and data transfer to a laptop PC. Prototype MATLAB software was used for setup and acquisition of time-domain data and subsequent processing of averaged frequency response functions (FRFs). Some difficulty was experienced due to the prototype nature of both the hardware and software for this system, which had been hurriedly assembled. It was generally agreed that a production system would provide convenient means for signal monitoring, troubleshooting and on-the-fly processing, and display. Once the difficulties were addressed, the system worked reliably.

A separate and redundant VXI-based data acquisition system running proprietary Boeing (Prism) software was used to measure comparison data that validated results obtained with the DSS. Also, since this DSS sample did not contain a source module, the VXI-based system was used to generate random signals that were used during the multiple input multiple output (MIMO) excitation runs. Continuous random noise was used for this purpose, and leakage was minimized through application of cyclic averaging.[2,3]

A total of 32 digital accelerometers (PCB 393M72) were built as prototypes for this test (Figure 3). These sensors attach directly to the digital bus ribbon cable and feature 1 V/g sensitivity response below 1 Hz, nominal 24-bit analog-to-digital conversion (A/D), and were equipped with TEDS memory on which was stored the transducer serial number and sensitivity. The remaining 30 accelerometers were conventional ICP®-type sensors connected by fairly short cable to three-channel digitizing modules, DSIT, as pictured in Figure 4.

All sensors incorporated so-called "smart sensor" technology, in which the transducer electronic data sheet (TEDS) is retained in memory in the sensor.[3] During acquisition setup, the acquisition software reads this memory from each sensor to obtain the transducer serial number and sensitivity. In this test, we had prepared in advance a table of the location number, direction, and geometry for each sensor. The serial numbers were manually recorded and entered at the time of sensor installation. No final end-to-end check of instrumentation was performed. (No evidence has been seen of sensor misidentification).

This TEDS feature clearly saves several minutes of installation time for each sensor and reduces the potential of human error. It was generally agreed that a process is desired to automate the association of serial number with location and direction. Also, the nominal 24-bit quantization demonstrated obvious value, since no time was spent setting or changing input ranges.

Number and Location of Sensors. At the time, a data system

Figure 3. Thirty-two prototype digital sensors were used.

Figure 4. DSIT three-channel digitizing module.

that was configured for 64 measurement channels was chosen for the test. Since 64 is considerably fewer sensors than are traditionally used for aircraft testing,[4-6] this provided an opportunity to explore the concept of a "minimalist sensor set." How many sensors are needed for modal testing? Given that it takes time to install sensors, there is a motivation to reduce the number to save time and cost. Kammer[7] showed an approach to locate one sensor per mode, coining the phrase "effective independence," motivated by the limitations of placing sensors on orbiting space vehicles. A cursory summary of alternative strategies was given in Reference 8. The independence of the estimated mode shapes was distinguished numerically using the MAC[9], and an intuitive wire frame animation display was created accordingly. The use of only 62 sensors at 39 locations was sufficient for this test, provided that the target modes were limited to about 10 Hz (20 modes) and that mode shape expansion is used to 'augment' our measured space.

Candidate sensor locations were identified by applying QR decomposition to the modal matrix from our pretest model and applying the approach of Schedlinski and Link.[10] Final locations are shown in Figure 5 and were determined by "engineering judgment" considering symmetry, co-locating biaxial or triaxial sensors where appropriate, and by considering the plan for geometry-based shape expansion.

With so few sensors, shape expansion is necessary to produce mode shapes that lend to intuitive interpretation. With concerns over the fidelity of the pretest model, a geometry-based method of expansion was used. Motion from selected degrees of freedom (DOFs) was copied to others or linearly interpolated based on assumptions about the behavior of the structure. Figure 6a shows an example using the raw measured mode shape using 62 DOFs at 39 locations; Figure 6b shows the result of geometric expansion, which provides full three-dimensional (3D) motion of 117 DOFs at the same 39 locations. Though it may not be obvious from these static figures, in animation, the expanded shape is far easier to interpret compared to the (unexpanded) raw shape.

The minimalist sensor set appears to have been very success-

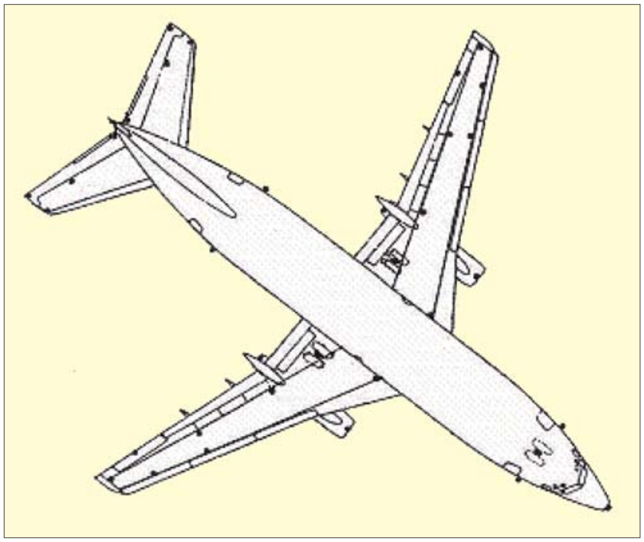

Figure 5. Location of 62 sensors at 39 locations, plan view.

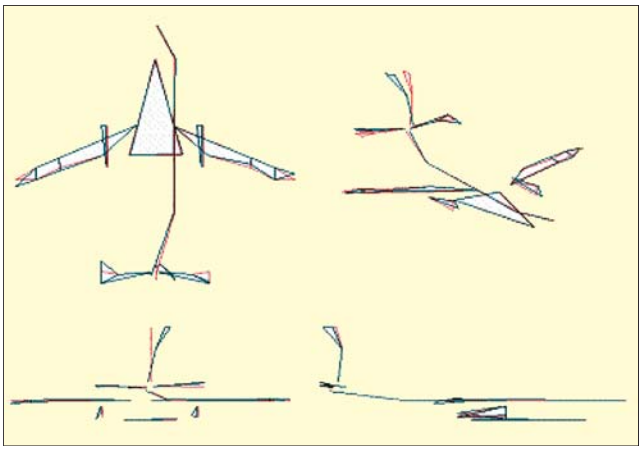

Figure 6a. Mode shape display of 62 measured DOFs at 39 locations.

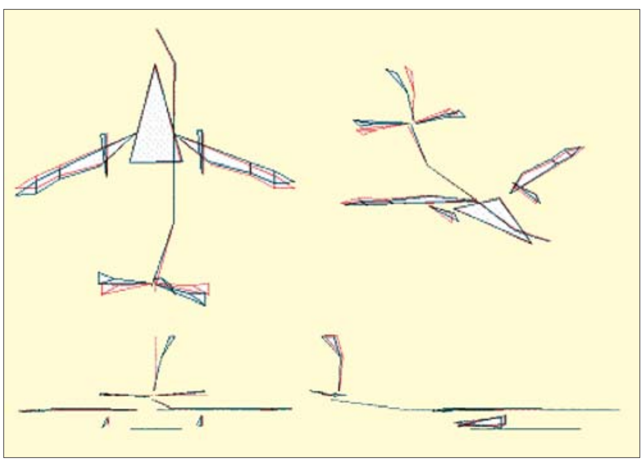

Figure 6b. Mode shape display of 62 measured DOFs, expanded to 117 DOFs at 39 locations.

ful. The auto-MAC of the first 19 modes to ~10 Hz, shown in Figure 7, has mostly low off-diagonal terms, and the animated shapes are depicted unambiguously once the expansion has been applied. It is also clear that more sensors would be needed to achieve the same independence and depiction at frequencies above 10 Hz.

Determining Geometry of Installed Sensors. One timesaving concept and the subject of much discussion concerns the physical location and orientation of accelerometers on the test structure. The locations are commonly predetermined using both the analysis pretest model grid points and structural drawings or 3D datasets. Considerable time and effort can be expended in

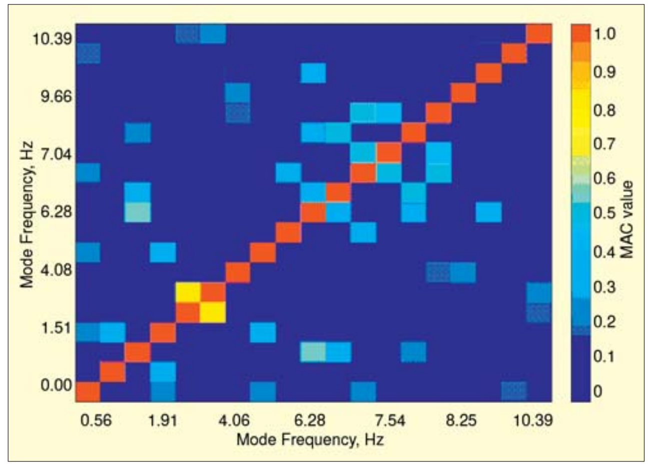

Figure 7. Auto-MAC of modes identified from MIMO random data set.

Figure 8. Shaker under wing tip.

locating and orienting sensors precisely, where mode shapes are to be used quantitatively in hybrid models or for model updating. Furthermore, each sensor may require several 'visits' by a test engineer or technician to locate, attach to structure, connect to cables, and perform an end-to-end identification check.

The concept was as follows:

- Predetermine sensor location from pretest mode shapes but with a generous tolerance for location.
- Install sensors quickly with minimal attention to location and oriented by convenience (eg., normal to surface).
- Measure to adequate precision the *in situ* locations and orientations (after attachment) using photogrammetry.[11-13]
- Use computing power and geometry to facilitate test-analysis comparisons.

Photographs were taken of the sensors. Unfortunately they were later found to be incomplete and unsuitable for this purpose. A reverse photogrammetry system with camera probe[14] was demonstrated. It could accurately locate sensors and their orientation over a several meter volume; however, this system was not designed for large structures such as a 737 airplane.

This is an area that shows considerable promise and is deserving of further efforts. It was widely agreed that an accurate *in situ* identification to document sensor locations is desirable as good measurement practice.

Excitation

Considerations for excitation include: frequency bandwidth; mode controllability; measurement accuracy; signal waveform as it minimizes, exacerbates, or reveals departures from linearity; cost; or convenience. The predominant modal testing approach[4-6] in airplane testing excites the structure using multiple shakers and either sine or random test signals. Motivated to explore simpler and less time-consuming approaches, we acquired several datasets using transient excitation techniques that have been applied successfully to other structures.

A baseline dataset was acquired using random excitation through two shakers – one vertical at each wing tip. Transient data were acquired using input vertical at the two wing tips, chord-wise at a wing tip, vertical at the stabilizer tip, and lateral on the forward nacelles. Transient input consisted of impact, step relaxation, and "manual harmonic input" (where a mode is harmonically excited by hand). Time-domain data were recorded for about 7 minutes at each location while the input was repeatedly applied. The structural response was allowed to decay after each input.

Shaker Excitation. A baseline dataset was acquired using random excitation through two shakers, one vertical at each wing tip (see Figure 8). The shakers were driven with uncorrelated, continuous random signals. FRFs were computed using the H_1 method.[15,16] Both cyclic and spectral averaging were used to reduce the effects of noise and leakage.[17] The reciprocal pair of FRFs between the wing tips is shown together with multiple coherence functions in Figure 9. The mode shapes derived from the MIMO random excitation are depicted in Figure 10.

Transient Excitation, Impact. One data set was acquired using an input force measurement from an instrumented hammer. The FRFs computed from these data compare favorably with the same measurements performed using MIMO dual-random excitation with shakers (see Figure 11). We conclude, for example, that the shaker-excited input measurements were free of stinger-induced dynamic interactions.

Transient Excitation, Free Decay. The data acquisition and processing approach we used for the transient excitation datasets represents a significant departure from the traditional airplane GVT approach. No forces were measured, and no FRFs were computed. Only time-domain transient responses were recorded. Modal parameter identification was performed using a time-domain algorithm similar to ERA,[15,16,18,19] yielding unscaled modes. Data from different input locations were treated as if from different references in the multireference algorithm. An example of the transient response is shown in Figure 12.

Transient free decays from many input locations were used individually or assembled into a single dataset, from which a global modal model was estimated. The Fourier transform was used to spectrally limit the bandwidth, and modes were estimated by frequency band, as shown in the example of Figure 13. Complex mode indicator functions (CMIFs)[20,21] were computed from the frequency-domain linear spectra.

An advantage of transient data acquisition is that it can be performed in a short time. It is also relatively easy to obtain a generous number of input locations, including locations where the use of shakers might be difficult or impractical. Engineers who are accustomed to using FRFs as a starting point for modal analysis may at first feel uncomfortable working with transient free decay measurements. The FRFs provide valuable mode indicator functions, and the reconstruction of FRFs provides an important validation of the estimated modal model.

Comparing Modes from Random vs. Transient. The mode shapes derived from transient excitation are compared with the mode shapes derived from MIMO random excitation in Figure 14, which shows the MAC[9] represented in color. The two sets of modes are actually very close, except for three modes:

- 8.63-Hz mode identified from the random dataset was missed in the transient analysis. We note this mode is predominantly horizontal stabilizer fore-aft motion (yaw).
- 8.95-Hz modes differ somewhat in shape. We note this mode also contains horizontal stabilizer fore-aft motion.
- 10.39-Hz modes differ somewhat in shape; the reason for this remains unexplained.

The fact that the 8.63-Hz mode was missing from the transient-derived modes was not discovered until after the test. Had this been noticed, presumably by comparison to a pre-test model, this degree of freedom could easily have been included in the dataset.

Nonlinear ID. A significant portion of many airplane GVTs is devoted to sine testing and moderate-to-high response amplitude.[4-6] The airplane modes are quickly identified from MIMO random excitation measurements. This set of modes was called a "small-signal model,"[5] reflecting the fact that the airplane structural response level was very low in amplitude. It is often necessary to identify a "large-signal model," where the structural response amplitude approximates operating conditions. As described in Reference 6, the entire data sets are measured at high amplitude, while in Reference 5, only a few modes are so identified.

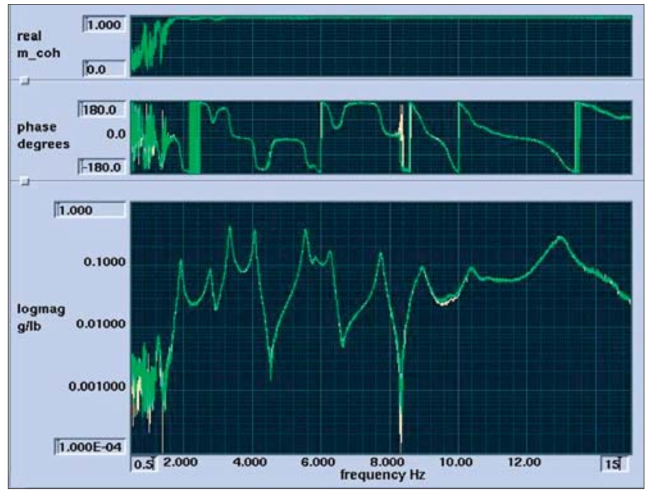

Figure 9. Example of reciprocal FRFs computed from MIMO random excitation with multiple coherence.

Identifying large-signal behavior usually consists of noting changes in the parameters (usually frequency and damping) as response amplitude is increased from small-signal test levels to higher levels representing operational environment (backbone curves). Traditionally this requires considerable test time using sine excitation. An important subject for future work is to identify as much as possible of this amplitude dependence from the transient free decay responses. Further, it will be important to consider these amplitude dependencies in the context of confidence and uncertainty intervals, including modeling errors, manufacturing variability, and knowledge of operating environment.

Conclusions

A collaborative demonstration and development test was performed on a 737-200 transport airplane, including participants from university, manufacturer, and vendor organizations. Concepts were explored and demonstrated which suggest the potential to significantly reduce the test flow time for aircraft GVT. Some of these concepts, such as transient excitation, have long been successfully applied to other structures but are new to airplane testing and will likely see increased use in the future.

The digital sensors and associated acquisition hardware clearly demonstrated the value and timesaving resulting from reduced cabling requirements. The TEDS sensors facilitate sensor identification and automate the calibration entry. The test team must still associate the sensor serial number with a geometric location, and assure that the sensing direction is correct. Work remains to implement approaches for nonlinear ID from transient and uncertainty assessment to reduce the time that is traditionally devoted to sine testing.

As test flow time is greatly reduced, so is the time for data assessment, modal analysis and model correlation. This increases the risk that anomalies or errors may go undiscovered until later. Successful test completion normally requires a complete modal analysis and validation and a convincing model correlation. Improvements are needed in the software tools for data assessment, visibility, validation, identification, and correlation, possibly aided by automation and autonomous components.

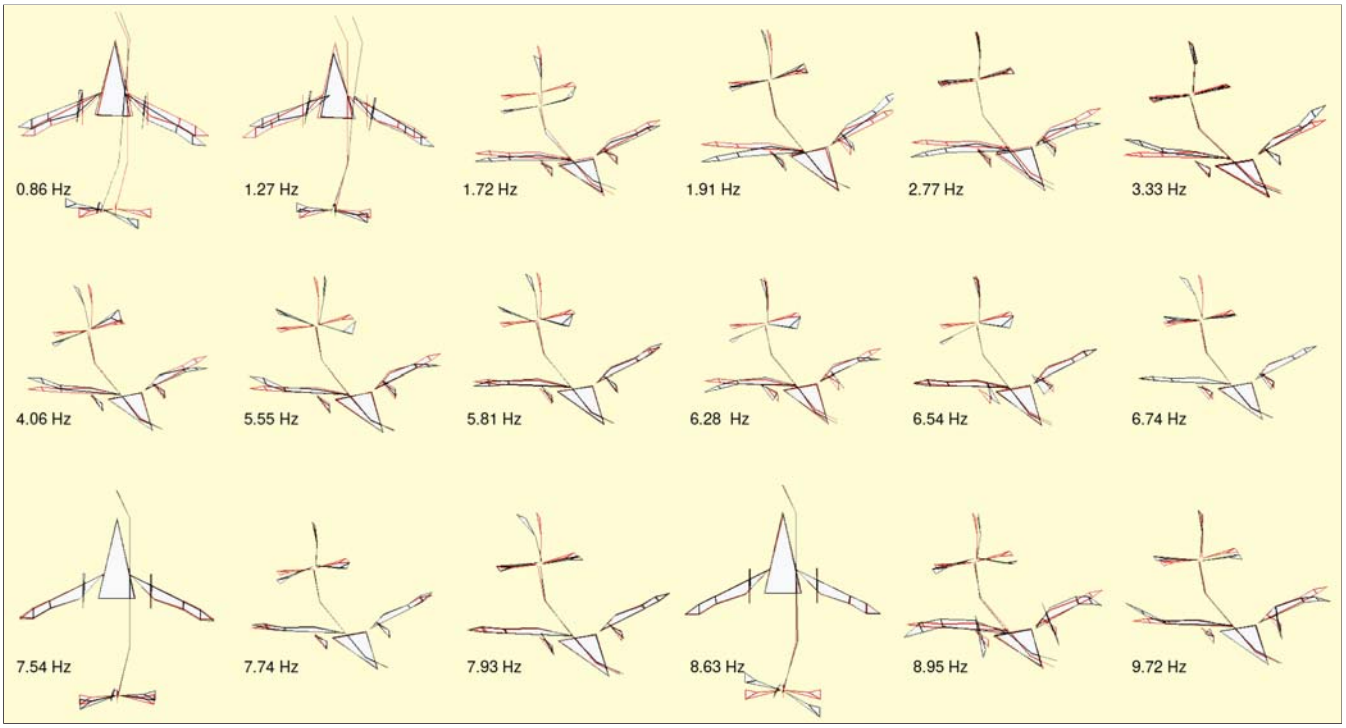

Figure 10. Shapes of modes identified from MIMO random excitation.

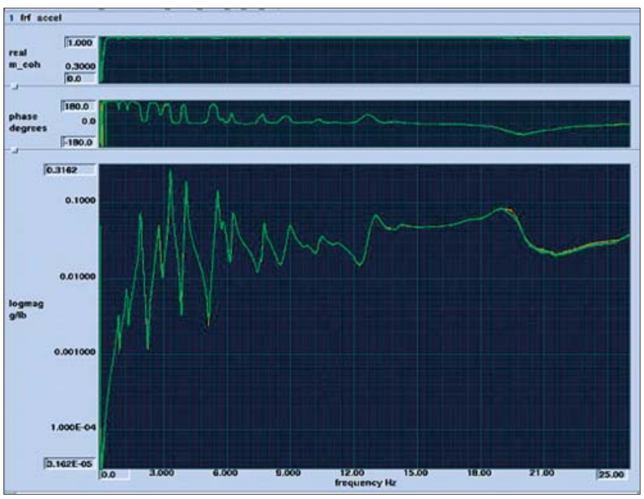

Figure 11. Driving point FRFs from different excitation types: green – MIMO dual random; orange – impact.

The diverse participants benefited from the opportunity to work together and share ideas in a practical and relevant test environment. The vendor and university participants were able to experience first hand the issues and challenges of testing a transport airplane. The manufacturer sponsors were exposed to new products and ideas. Freed from the usual pressures and unconstrained by tradition and habits, the manufacturer sponsors were able to take risks and try new approaches.

Acknowledgments

We wish to express our appreciation to all who helped make this test possible: PCB Piezotronics loaned the sensors; The Modal Shop loaned and demonstrated a photogrammetry system; Larson Davis loaned and operated the digital data system; Boeing Phantom Works loaned us the 737-200 airplane; Galvin Flying Service accommodated us in their hangar space; and the MATLAB acquisition software was written and supported by Dan Lazar of UC-SDRL, who also helped conduct the test. Many engineers from diverse organizations in the Boeing Company contributed their time and ideas. We appreciate the helpful comments and observations of Prof. Carlos Ventura of University of British Columbia, who visited during testing.

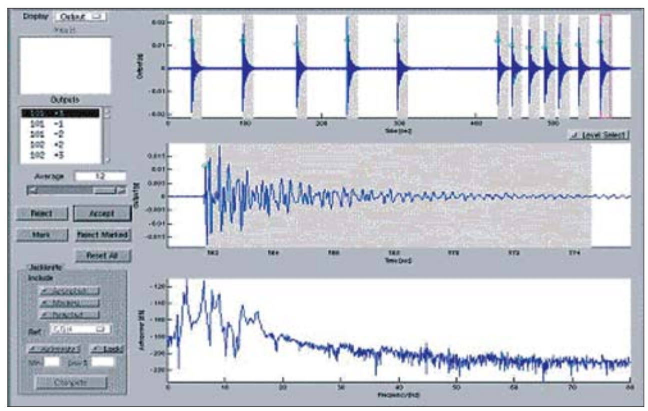

Figure 12. Transient response and spectrum.

References

1. "DSS Digital Sensing System," http://www.larsondavis.com/docs/DSS-1203_D0501_0009_REVB.pdf.
2. Cox, K., and Davis, L, "Simplified Transducer Cabling Using Digital Techniques," Proceedings of the 19th International Modal Analysis Conference, 2001.
3. Hunt, D., and Brillhart, R., "Smart Sensors, Dumb Engineers – How to Avoid Crossed Signals in Instrumentation," Proceedings of the 20th International Modal Analysis Conference, 2002.
4. Dotson, B. F., Brown, D. L., Michalak, R. F., Allemang, R. J. and Gimmestad, D., *Optimum Ground Vibration Test Method*, AFWAL contract F33615-77-C-3059, 1979.
5. Pickrel, C. R., "Ground Vibration Testing of Transport Aircraft: Correlation with a Nominal Linear Model," Proceedings Of 20th International Modal Analysis Conference, Los Angeles, CA 2002.
6. Dieckelman, R. J., "Modern Sine Excitation GVT Techniques," Proceedings of the 20th International Modal Analysis Conference, Los Angeles, CA 2002.
7. Kammer, D. C, "Sensor Placement for On-Orbit Modal Identification and Correlation of Large Space Structures," *AIAA Journal of Guidance, Control and Dynamics*, Vol. 14, No. 2, pp. 251-259, 1991.
8. Pickrel, C. R., "A Practical Approach to Modal Pretest Design," *Mechanical Systems and Signal Processing*, V. 13, No. 2, pp. 271-295,1999,.
9. Allemang, R. J., and Brown, D. L., "A Correlation Coefficient for Modal Vector Analysis," Proceedings 1st International Modal Analysis Conference, Orlando, FL, pp. 110-116, 1982.

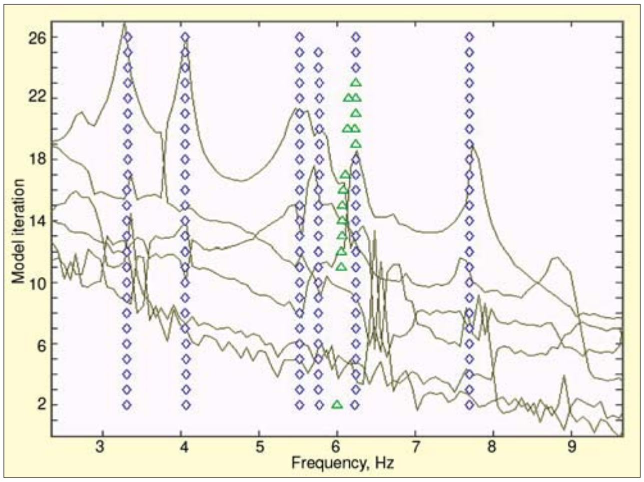

Figure 13. Consistency diagram for transient data.

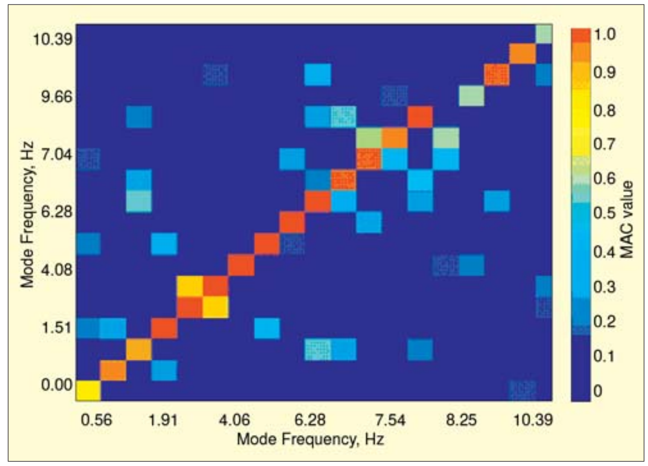

Figure 14. Cross-MAC comparing mode shapes derived from: y axis – transient excitation; x-axis – MIMO dual-random excitation.

10. Schedlinski, C., and Link, M., "An Approach to Optimal Pick-up and Exciter Placement," Proceedings of the 14th International Modal Analysis Conference, Dearborn, MI,1996.
11. Pappa, R. S., Giersch, L. R., and Quagliaroli, J. M., "Photogrammetry of a 5m Inflatable Space Antenna with Consumer Grade Digital Cameras," *Experimental Techniques*, Vol. 25, No. 4, pp. 21-29, July/Aug, 2002.
12. Pappa, R. S., Black, J. T., and Blandino, J. R., "Dot-Projection Photogrammetry and Videogrammetry of Gossamer Space Structures," Proceedings of the International Modal Analysis Conference, 2003.
13. Foss, G. C., "Photogrammetry of Aircraft Structures for Sensor Location," Proceedings of the 23rd International Modal Analysis Conference, 2005.
14. Dillon, M. J., and Brown, D. L., "Use of Photogrammetry for Sensor Location and Orientation"
15. Phillips, A., and Pickrel, C., Philosophy, Design, Implementation and Application of Modal Analysis Software System," *Proceedings of the 12th International Modal Analysis Conf*erence, Honolulu, HI 1994.
16. Allemang, R. J., Brown, D. L., and Fladung, W, "Modal Parameter Estimation: A Unified Matrix Polynomial Approach," Proceedings of the 12th International Modal Analysis Conference, Honolulu, HI, pp. 501-514, 1994.
17. Phillips, A. W., Zucker, A. T., and Allemang, R. J., "Frequency Resolution Effects on FRF Estimation: Cyclic Averaging vs. Large Block Size," Proceedings of the XVII International Modal Analysis Conference, 1999
18. Ibrahim, S. R., Mikulcik, E. C., "A Method for the Direct identification of Vibration Parameters from Free Response," *Shock and Vibration Bulletin*, Vol. 47, Part 4, pp. 183-198, 1977.
19. Juang, J. N., and Pappa, R. S., "An Eigensystem Realization Algorithm for Modal Parameter Identification and Model Reduction," *AIAA Journal of Guidance, Control and Dynamics*, Vol. 8, No. 4, 1985, pp. 620-627.
20. Ewins, D. J., *Modal Testing: Theory, Practice and Application*, Research Studies Press, 2000.
21. Allemang, R. J., Brown, D. L., and Rost, R. W., "Experimental Modal Analysis and Dynamic Component Synthesis," Wright Aeronautical Laboratories Report AFWAL-87-3069, 1987.

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