Quiet Spike™ Build-up Ground Vibration Testing Approach

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Flight tests of Gulfstream Aerospace Corporation's Quiet Spike™ hardware were recently completed on the NASA Dryden Flight Research Center F-15B airplane. NASA Dryden uses a modified F-15B airplane as a testbed aircraft to cost-effectively fly flight research experiments that are typically mounted underneath the F-15B airplane, along the fuselage centerline. For the Quiet Spike™ experiment, however, instead of a centerline mounting, a relatively long forward-pointing boom was attached to the radar bulkhead of the F-15B airplane. The Quiet Spike™ experiment is a stepping-stone to airframe structural morphing technologies designed to mitigate the sonic-boom strength of business jets over land. The Quiet Spike™ boom is a concept in which an aircraft's noseboom would be extended prior to supersonic acceleration. This morphing effectively lengthens the aircraft, thus reducing the peak sonic-boom amplitude, but is also expected to partition the otherwise strong bow shock into a series of reduced-strength, noncoalescing shocklets. Prior to flying the Quiet Spike™ experiment on the F-15B airplane several ground vibration tests were required to understand the Quiet Spike™ modal characteristics and coupling effects with the F-15B airplane. However, due to the flight hardware availability and compressed schedule requirements, a "traditional" ground vibration test of the mated F-15B Quiet Spike™ ready-for-flight configuration did not leave sufficient time available for the finite element model update and flutter analyses before flight testing. Therefore, a "nontraditional" ground vibration testing approach was taken. This paper provides an overview of each phase of the "nontraditional" ground vibration testing completed for the Quiet Spike™ project which includes the test setup details, instrumentation layout, and modal results obtained in support of the structural dynamic modeling and flutter analyses.

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Nomenclature

CG	=	center of gravity
FE	=	finite element
Fwd	=	forward
GAC	=	Gulfstream Aerospace Corporation (Savannah, Georgia)
GVT	=	ground vibration test
Mid	=	middle
QS	=	Quiet Spike™

I. Introduction

Gulfstream Aerospace Corporation (GAC) (Savannah, Georgia) recently completed flight-testing of their Quiet Spike™ (QS) technology on the NASA Dryden Flight Research Center F-15B airplane.[1] The QS experiment is a stepping-stone to airframe structural morphing technologies designed to mitigate the sonic-boom strength of business jets over land.[2-5] Before the QS experiment was granted flight clearance on the F-15B airplane, several ground vibration tests were required to understand the QS modal characteristics and coupling effects with the F-15B airplane. However, due to the flight hardware availability and compressed schedule requirements, a "traditional" ground vibration test (GVT) of the mated F-15B QS ready-for-flight configuration did not leave sufficient time available for the finite element (FE) model update and flutter analyses before flight-testing. Therefore, a "nontraditional" ground vibration testing approach was taken.

The objective of the QS build-up ground vibration testing approach was to obtain confidence in the final F-15B QS FE model to be used for flutter analysis. To develop the F-15B QS FE model with reliable foundation stiffness between the QS and F-15B radar bulkhead and QS modal characteristics, several different GVT configurations were utilized, as shown in Fig. 1. Each of the four performed GVT phases had a specific objective. The overall intent was to provide adequate data that would replicate a "traditional" F-15B QS mated GVT with actual flight-ready hardware. The NASA Dryden Flight Research Center was in charge of conducting the 1st, 2nd and 4th GVT phases; the 3rd GVT phase was GAC's responsibility. For the build-up GVT approach to be feasible, it was critical that each GVT configuration matched as closely as possible the structural connection interface between the QS and the F-15B radar bulkhead.

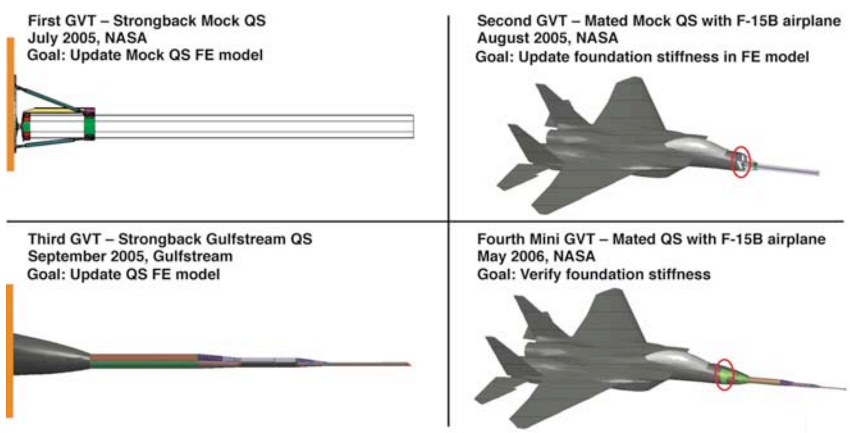

Figure 1. The QS build-up ground vibration testing approach.

To conduct the 1st and 2nd GVT phases, a mock-up version of the QS boom was designed and fabricated with similar weight, center of gravity (CG) and moment of inertia characteristics as the flight configuration of the fully extended QS. As shown in Fig. 1, the 1st GVT performed was the Strongback Mock QS GVT with the goal of updating the analytical Mock QS FE model based on GVT results. This 1st GVT and FE model update assumed a rigid connection between the Mock QS root plane and the strongback.

The 2nd GVT phase involved the Mock QS mated with the F-15B airplane, and characterized the spring stiffness for the connection between the Mock QS root plane and the F-15B radar bulkhead. Since the Mock QS FE model, with a rigid connection at the root plane, was already correlated to the data from the 1st GVT, the only design variable needed to update the Mock QS FE model from the data of the 2nd GVT was the foundation stiffness between the Mock QS root plane and radar bulkhead.

The 3rd GVT phase was very similar to the 1st GVT phase with respect to the use of a rigid connection, but was performed on the actual QS flight hardware at GAC. The data from the 3rd GVT was used to update the extended QS FE model and, later, a retracted QS FE model was analytically generated from this extended QS FE model. Following the extended QS FE model update, the foundation spring stiffness established from the 2nd GVT was included in both the extended and retracted QS FE models and separately attached to the F-15B FE model. This connection stiffness between the airplane radar bulkhead and QS test article was the unknown structural dynamic factor that drove this sequence of testing, see Fig. 2. This combined F-15B QS FE model was used as a baseline model for parametric variations in F-15B QS foundation stiffness for the flutter sensitivity analyses.

The 4th GVT performed was on the QS mated to the F-15B airplane: the final flight configuration. This last GVT was considered a mini-GVT because only a minimal number of accelerometers were used, which provided insufficient data for updating a FE model. The first objective of this final GVT was to measure the primary frequencies of the extended QS on the F-15B airplane for validation of the foundation spring stiffness. The second objective was measurement of the primary frequencies of the retracted QS to verify that the retracted QS FE model configuration was correctly modeled. The final GVT data was also used to determine which flutter analysis was appropriate to select from the flutter sensitivity study.

This paper provides an overview of each phase of the “nontraditional” ground vibration testing completed for the QS project, which includes the test setup details, instrumentation layout, and modal results obtained in support of the structural dynamic modeling and flutter analyses.

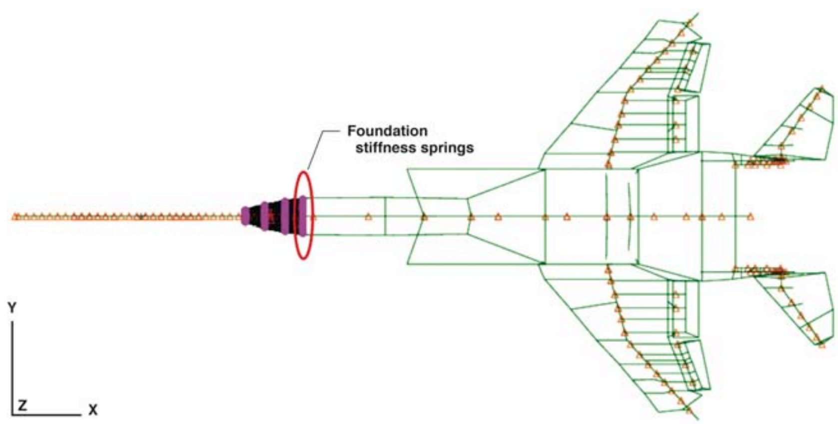

Figure 2. The FE model with unknown connection stiffness between the QS and the F-15B airplane.

II. Mock Quiet Spike™, Quiet Spike™, and Supporting Hardware

To perform the 1st and 2nd GVTs, a mock-up version of the QS boom was designed and fabricated with similar weight, CG and moment of inertia characteristics to that of the anticipated fully extended configuration of the QS flight hardware. The Mock QS, which represents the modal characteristics of the extended QS position, was a 19-ft-long fixed, aluminum, welded structure, as illustrated in Fig. 3. Along with similar modal characteristics, the Mock QS was also designed to interface with the same support structure hardware that was used to mount the QS to the F-15B radar bulkhead. The weight of the Mock QS boom represented the QS boom as well as the custom-designed QS radome and radome bulkheads. The moment of inertia of the Mock QS was designed as closely as possible to match the aft boom segment (16 in. diameter) of the QS. The Mock QS boom CG location was designed to match as closely as possible the fully extended QS boom model.

Gulfstream Aerospace Corporation's QS boom consisted of three segments: the forward, middle, and aft boom. The forward boom (4 in. diameter) and the middle boom (10 in. diameter) extends and retracts; the aft boom (16 in. diameter) was a fixed segment (see Fig. 3). From the QS attachment location on the airplane radar bulkhead the fully extended QS was approximately 30 ft long and the retracted QS was approximately 20 ft long. The aft 6-ft section of the boom was enclosed in a custom-designed radome.

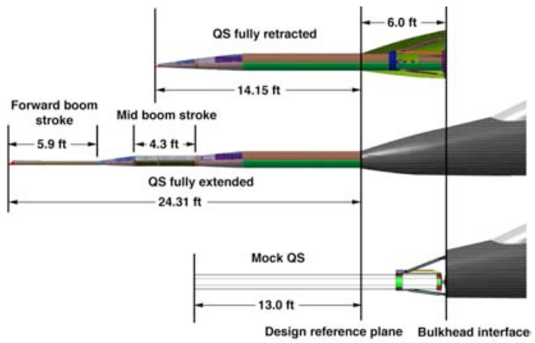

Figure 3. Comparisons of the retracted or extended QS and Mock QS.

As shown in Fig. 4, the Mock QS was designed to interface with the same supporting structure hardware that was used to mount the QS to the F-15B radar bulkhead so that the QS load path and stiffness characteristics could be replicated as closely as possible. Figure 5 shows the four locations on the attachment ring and the 19 locations on the intermediate bulkhead, which interfaced with either the F-15B radar bulkhead or the strongback. For flight, the main loads were carried through the four attachment ring locations. It was critical that each GVT configuration had the same connection interface so that the interface stiffness could be accurately measured. All bolts in this interface connection between the supporting structure and either the strongback or F-15B bulkhead were torqued to consistent values, as shown in Fig. 5.

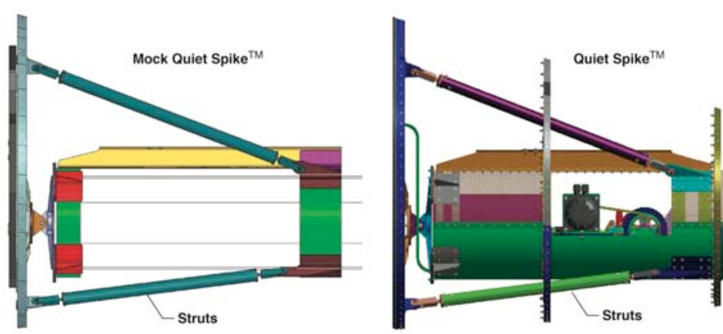

Figure 4. The identical supporting structure used for the Mock QS and the QS GVTs.

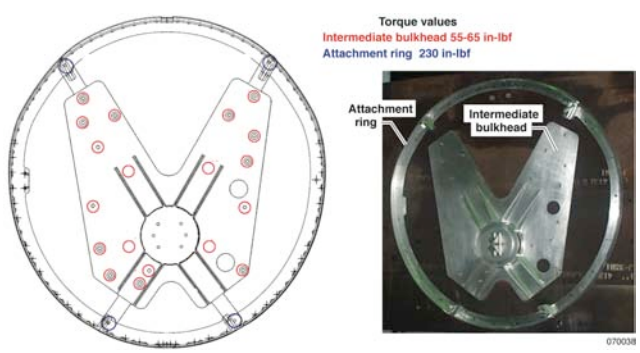

Figure 5. The supporting structure attachment locations and torque values.

III. First Ground Vibration Test: Strongback Mock Quiet Spike™

The 1st GVT performed in the build-up GVT approach was the Strongback Mock QS GVT with the goal of updating the Mock QS FE model based on GVT results.[6] A rigid connection between the Mock QS root plane and the strongback was assumed for the FE model and the 1st GVT phase. The QS project was also interested in understanding the relationship between the Mock QS frequencies when the struts were loaded differently.

A. First Ground Vibration Test: Setup

The Mock QS was mounted on a 1-in.-thick steel strongback fixture in NASA's Flight Loads Laboratory, as shown in Fig. 6. Different bolts with a longer shank length were required for the 19 intermediate bulkhead bolts and the four attachment ring bolts for mounting on the strongback. The material and strength of the bolts were identical to the bolts being used on the airplane radar bulkhead; only the shank lengths were longer to accommodate the thick steel plate of the strongback. No spacers were used on the strongback to offset the intermediate bulkhead; therefore, the intermediate bulkhead and the attachment ring were in full contact with the strongback. An additional diagonal I-beam was installed on the left side of the strongback (see Fig. 7) after initial test data indicated the strongback rigidity in the lateral direction was inadequate.

Figure 6. The Strongback Mock QS GVT configuration.

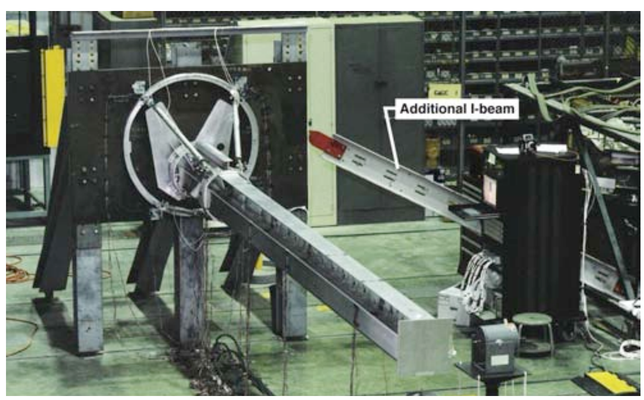

Figure 7. The additional lateral I-beam on the strongback.

B. First Ground Vibration Test: Instrumentation

This testing configuration had a total of 120 accelerometers between the Mock QS and the strongback (see Fig. 8). The Mock QS boom was instrumented with 60 accelerometers in the vertical and lateral directions and which were placed on the right-hand side of the top-welded T-beam as close as possible to the center rod (see Fig. 9). A few accelerometers were placed in similar locations on the bottom T-beam on the left-hand side of the Mock QS boom to capture the torsion mode. Each of the four strut assemblies on the supporting structure had four different accelerometer locations with accelerometers in all three directions for a total of 48 strut accelerometers. The strongback was instrumented with 12 accelerometers, which monitored the strongback movement and identified the need for the additional diagonal I-beam support on the strongback.

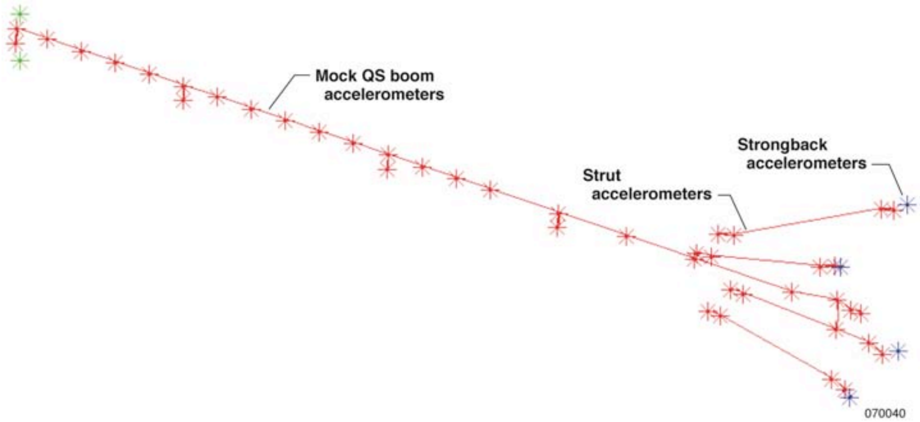

Figure 8. The Mock QS boom accelerometer locations.

Figure 9. The Mock QS boom accelerometers.

To obtain the "cleanest" mode shapes for mode matching, the shakers were oriented in the direction of the Mock QS known deflections (lateral and vertical). The vertical excitation was applied just aft of the square plate on the center of the bottom T-beam and the lateral excitation was applied on the center of the left T-beam, as shown in Fig. 10. To match the required height to the Mock QS boom, the shakers were placed on custom-built shaker stands that were screwed into short standard 10-ton aircraft jacks. The shakers were bolted onto the shaker stands, and lead shot bags were used to weigh down the aircraft jacks.

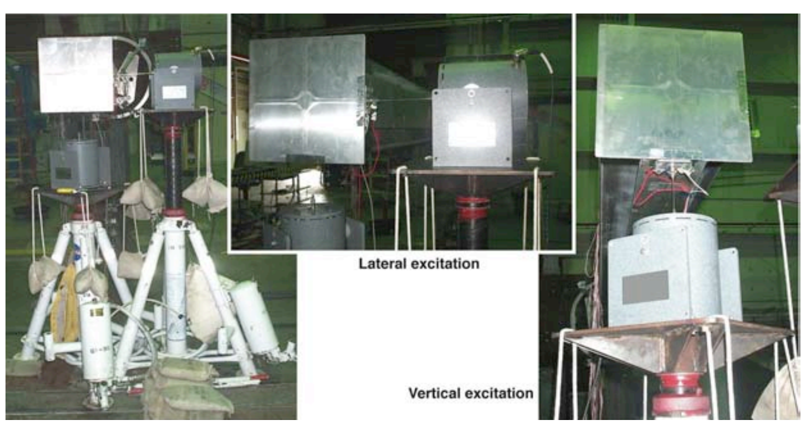

Figure 10. The shaker setup for the Strongback Mock QS GVT.

Because of the uncertainty of the strut load effect on the Mock QS frequencies and mode shapes, each of the four strut assemblies in the supporting structure hardware were instrumented with primary and secondary strain gages to allow the strut and clevis loads to be monitored during testing operations (see Fig. 11). The range of strut loads examined was directly dependent on the axial load at the clevis pivot point. The Mock QS support hardware connected to the clevis pivot point was designed primarily for vertical loads, so only a small axial load could be applied to the clevis. The clevis hardware was not instrumented; however, the clevis axial and vertical loads were calculated from the strut strain gages, several geometrical dimensions, the weight, and the CG location of all the hardware forward of the clevis pivot point. The range of strut loads tested was derived from three different clevis axial load configurations: a zero axial clevis load, a -560 lb compression axial clevis load, and a 560 lb tension axial clevis load.

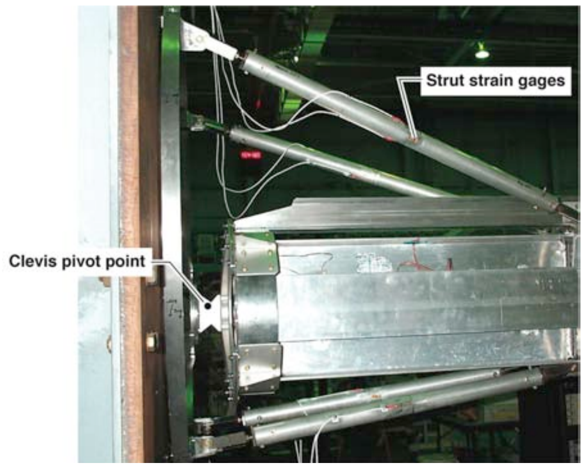

Figure 11. The strut strain gages and clevis pivot pin locations.

C. First Ground Vibration Test: Configurations and Results

For the Strongback Mock QS GVT, several testing configurations (1-A to 1-F), shown in Table 1, were performed because of the uncertainty of the strut loading effect on the Mock QS frequencies and mode shapes. Both the vertical and lateral shaker configurations were excited with a burst random input at three different force levels. A total of 22 test runs were completed in the 1st GVT configuration. Several of these data sets were curve fit, analyzed and compared. Very little effect was seen in the Mock QS frequencies and mode shapes when varying the strut loads that ultimately changed the clevis axial load.

Table 1. The Strongback Mock QS GVT configurations.

Conf.	**Excitation Direction**		**Clevis Axial Load (lb)**		
	Vertical	Lateral	0	560	-560
1-A	X		X		
1-B		X	X		
1-C	X			X	
1-D		X		X	
1-E	X				X
1-F		X			X

Configurations 1-A and 1-B were conducted in the zero axial clevis load configuration, which were the nominal strut loads for flight. Several GVTs with different force levels were performed in each configuration. These data sets were then curve fitted and the "best" mode shape results were chosen for mode matching and updating the equivalent Mock QS beam FE model. Configuration 1-A, with the vertical shaker excitation, excited the 1st vertical bending mode of the Mock QS. Lateral excitation was used in configuration 1-B where the 1st lateral bending and torsion modes were extracted. The frequency response function from these two data sets shows two strong peaks for the Mock QS 1st lateral and vertical bending modes and a weak peak for the Mock QS torsional mode. The torsional mode was not prevalent and seemed to be very sensitive to the test setup. The Mock QS FE model correlation process matched this torsional mode, but was not really necessary because the flight QS hardware torsional mode was presumed to be very high due to the radome stiffness and geometry differences between the Mock QS and actual QS. The main two modes of interest to the QS project were the 1st lateral and 1st vertical bending modes at 5.58 Hz and 7.75 Hz, respectively. The GVT mode shapes shown in Fig. 12 were used for updating the analytical beam Mock QS FE model, which was the goal of this 1st GVT phase in the QS build-up GVT approach.

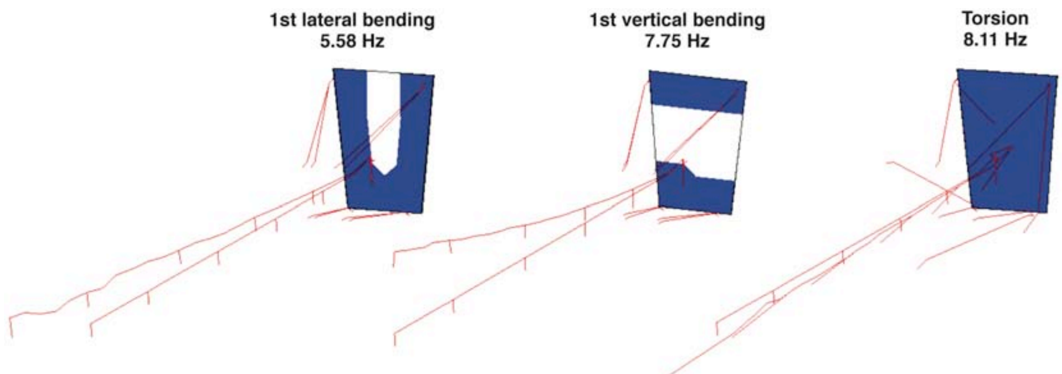

Figure 12. The mode shapes of the Strongback Mock QS used for model correlation.

III. Second Ground Vibration Test: Mated Mock Quiet Spike^{TM} with F-15B Airplane

The 2nd GVT in the QS build-up ground vibration testing approach involved the Mated Mock QS with the F-15B airplane. This 2nd test characterized the spring stiffness for the connection between the Mock QS and the F-15B radar bulkhead. Since the Mock QS FE model, with a rigid connection, was already correlated to the data from the 1st GVT, the only design variables required to update the Mock QS FE model were the spring constants between the Mock QS and airplane radar bulkhead[6]. The spring constants for the connection between the Mock QS and airplane radar bulkhead were a significant unknown and very difficult to model correctly, thus, the goal of the 2nd GVT phase was to characterize them by measurement.

A. Second Ground Vibration Test: Setup

The Mock QS was mounted on the radar bulkhead of the F-15B airplane. The airplane was restrained by tracks in the hangar floor during testing. Prior to mounting the Mock QS onto the airplane, 1-in.-thick aluminum plates were installed to ensure that the attachment ring and intermediate bulkhead were aligned correctly, as shown in Fig. 5. After the Mock QS was mounted on the F-15B radar bulkhead, the airplane was leveled on jacks in an empty fuel configuration with the landing gear down, as shown in Fig. 13. The vertical constraints and lateral constraint structures were then installed.

Figure 13. The Mated Mock QS with the F-15B GVT configuration.

Since the NASA Dryden soft support system, which would simulate a free-flight environment, was not available for this GVT, standard F-15B jacks were used to support the airplane. The airplane was jacked upward just enough to enable the landing gear tires to have some clearance from the floor. The orientation of each jack during testing was critical because pretest analysis with jacked boundary conditions showed a difference in results based on the jack orientation. All three jacks were oriented with the front two legs perpendicular to the fuselage and the third leg pointed aft along the centerline of the fuselage.

To decouple and raise the airplane structural modes away from the Mock QS modes of interest, several aircraft constraints were used. Three vertical constraints were placed on the airplane, one on the aft centerline of the fuselage, one on each wingtip, and one on each horizontal stabilizer. Three symmetric lateral constraints were installed along the forward and aft fuselage. All constraints were positioned on primary airplane structure. Figure 14 shows the F-15B FE model grid locations of the lateral and vertical constraints. The airplane was tested in an empty fuel configuration so that the lateral constraint structures would not have to restrain the lateral motion of a fully-fueled airplane.

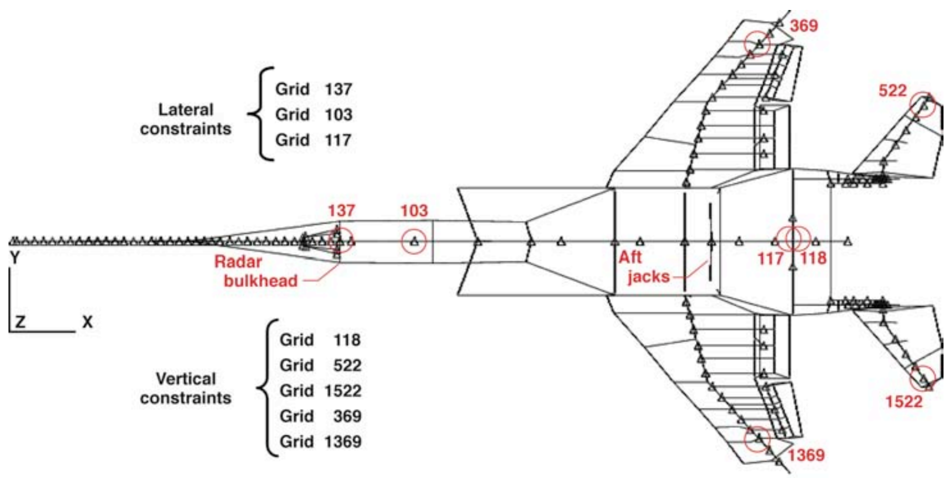

Figure 14. The grid locations of the aircraft constraints on the finite element model.

The vertical constraints used on the wingtips (grids 369 and 1369) were applied by padded supports that fit directly onto standard aircraft jacks. The vertical constraints used on the tip of the horizontal stabilizers (grids 522 and 1522) were applied with padded leading edge flap stands. The last vertical constraint was placed on the centerline of the airplane near the aft end of the arresting hook arm area (grid 118) with a wooden block and an aircraft jack. The vertical constraint jacks were raised to provide a snug fit, as shown in Fig. 15.

Figure 15. The aircraft vertical constraints.

The three lateral constraints were applied symmetrically (left and right) along the fuselage waterline CG using two back-to-back steel C-channels which were secured to the hangar floor tracks, see Fig. 16. The lateral constraint structures were installed near the airplane and then pulled in snug against the airplane. Initially, a thin layer of plywood was placed between the airplane structure and the steel I-beam to protect the airplane, however, after some initial testing the plywood was removed and replaced with a thin aluminum sheet. The lateral constraints did not induce large loads on the airframe and only prevented lateral motion.

The forward fuselage area was constrained by two lateral constraint structures (grids 137 and 103). The forward constraint structure was located at the radar bulkhead where the Mock QS was attached. The middle constraint structure was approximately 7 ft aft of the radar bulkhead on a structural bulkhead. The forward and middle constraint structures were connected with one horizontal and one diagonal unistrut brace to stabilize the two constraint structures. The aft lateral constraint structure was installed on the fuselage area just behind the flap trailing edge (grid 117). The aft constraint structure had a C-channel beam in the x-direction to stabilize the structure. All of the constraint structures were modified after the initial test data was analyzed. An additional longer diagonal I-beam in the y-direction was installed higher on the airplane near the actual contact point on the airplane surface. This modification to the aircraft lateral constraints provided boundary conditions similar to those analytically modeled.

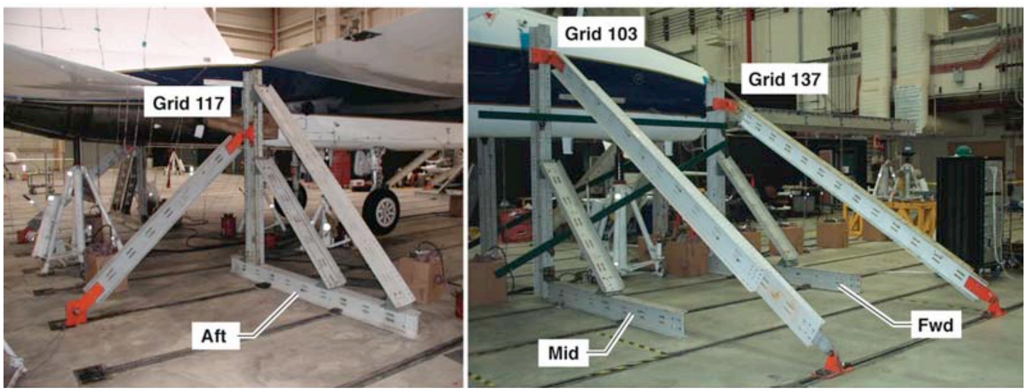

Figure 16. The aircraft lateral constraint structures.

B. Second Ground Vibration Test: Instrumentation

The 2nd GVT configuration had a total of 188 accelerometers between the Mock QS, F-15B, jacks and aircraft constraints; see Fig. 17 for the GVT model and accelerometer layout. The Mock QS had 54 of the same accelerometers from the 1st GVT, but all the strut and supporting structure accelerometers were removed for the 2nd GVT. An additional 15 accelerometers were placed on the attachment ring in four different locations and on the intermediate bulkhead. Near the attachment ring and intermediate bulkhead, other accelerometers were placed on the airplane radar bulkhead to use as a comparison of the Mock QS and airplane radar bulkhead connection. The response of the F-15B was captured with 84 accelerometers distributed over the airplane to monitor its movement. The three aircraft jacks were instrumented with six accelerometers, three accelerometers were on the vertical centerline constraint jack, and 26 accelerometers were attached to the lateral constraint structures.

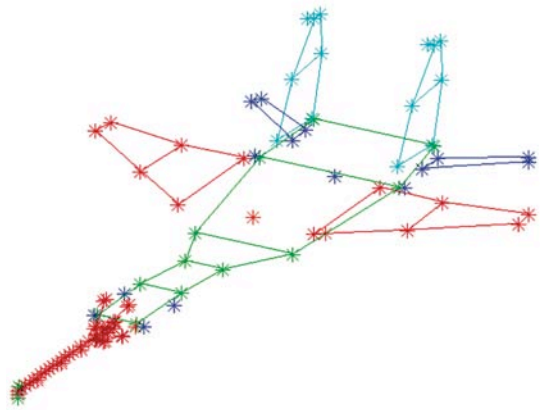

Figure 17. The Mated Mock QS with the F-15B GVT model.

For the 2nd GVT, burst random shaker excitation was used at the exact same vertical and lateral locations on the Mock QS boom used during the 1st GVT phase. The only difference was that the shaker jack stands were placed on steel stands to get the necessary height requirement due to the airplane being on jacks, see Fig. 18.

Figure 18. The shaker setup for the GVT of the Mated Mock QS with the F-15B airplane.

C. Second Ground Vibration Test: Configurations and Results

For the Mated Mock QS with the F-15B GVT phase, 14 different shaker/airplane configurations (2-A to 2-N) were tested, see Table 2. All configurations tested had the airplane in an empty fuel configuration with the landing gear extended and excited using a burst random input. For configurations 2-A to 2-L, the airplane was leveled on jacks and constrained with the vertical and lateral aircraft constraints. The configurations varied the excitation direction, clevis axial loads, and the number of bolts that connected the intermediate bulkhead to the airplane radar bulkhead. Three different intermediate bulkhead bolt patterns (19, 9, and 5 bolts) were tested to see how much the QS connection stiffness to the airplane radar bulkhead would change when removing some of the bolts. Upon completion of test configurations 2-A to 2-L the aircraft jacks, lateral constraint structures, and vertical constraints were removed. The landing gear tires were deflated to the lowest allowable pressure to obtain the soft tire boundary condition for test configurations 2-M and 2-N. The soft tire airplane configuration was a last-minute addition to the 2nd phase of testing to see if the Mock QS modes of interest were decoupled from the airplane modes with a soft boundary condition. A total of 50 data test runs were completed with the Mock QS attached to the F-15B airplane.

Table 2. The GVT configurations of the Mated Mock QS with the F-15B airplane.

Conf.	Excitation Direction		Clevis Axial Load (lb)			Boundary Condition				Intermediate Bulkhead Bolts		
	Vertical	Lateral	0	560	-560	Constraints with Plywood	Constraints with Metal	On Jacks	On Soft Tires	19	9	5
2-A	X		X			X		X		X		
2-B		X	X			X		X		X		
2-C		X	X				X	X		X		
2-D	X		X				X	X		X		
2-E	X			X			X	X		X		
2-F		X		X			X	X		X		
2-G		X			X		X	X		X		
2-H	X				X		X	X		X		
2-I	X		X				X	X			X	
2-J		X	X				X	X			X	
2-K	X		X				X	X				X
2-L		X	X				X	X				X
2-M	X		X						X	X		
2-N		X	X						X	X		

Configurations 2-C and 2-D were tested on the airplane in the zero axial clevis load configuration. In these two configurations, numerous data sets were collected with different shaker force levels along with several different zero clevis loading attempts to check for repeatability. These data sets were then curve fitted and the cleanest data and clearest mode shape were chosen for mode matching and updating the connection springs in the Mock QS FE model. The 2nd GVT results used for model updating were the 1st lateral bending mode (6.06 Hz) from the lateral excitation and the 1st vertical bending mode (7.75 Hz) from the vertical shaker excitation. Neither the frequency response function nor the mode indicator function from the lateral excitation showed a peak from the torsion mode as it previously did when the Mock QS was mated on the strongback. The mode indicator function is a visual indication of the modal density from a linear combination of the frequency response from all the accelerometers on the Mock QS boom and the F-15B airplane. The mode shapes shown in Fig. 19 were used for updating the connection springs in the beam Mock QS FE model.[6]

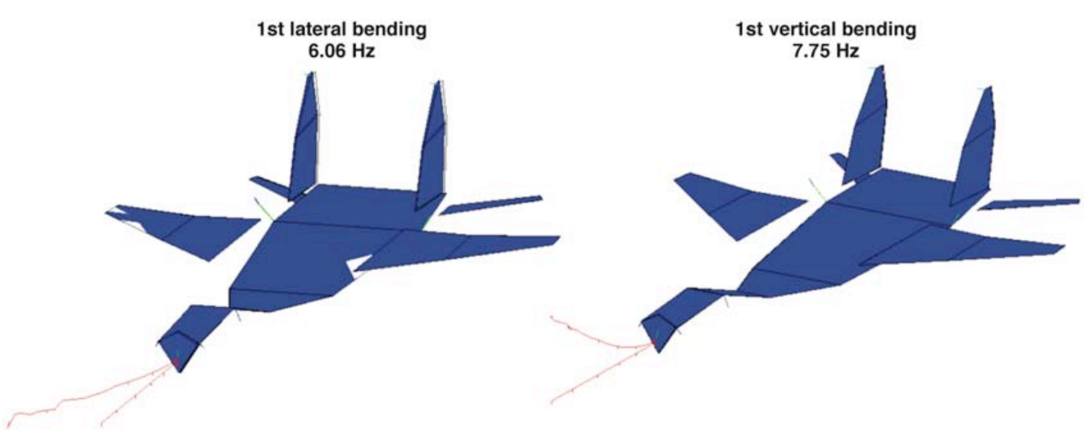

Figure 19. The mode shapes of the Mated Mock QS with the F-15B airplane constrained and on jacks.

IV. Third Ground Vibration Test: Strongback Quiet Spike™

The 3rd GVT phase performed for the QS build-up testing approach was similar to the 1st GVT phase with respect to using a rigid connection, but the 3rd GVT testing phase was performed on the actual QS at GAC. The GAC QS GVT data was used to update the extended QS FE model with a retracted QS FE model being analytically generated from the GVT correlated extended QS FE model. Following the extended QS FE model to GVT correlation, the connection springs established from the 2nd GVT were included in both the extended and retracted QS FE models and separately attached to the Dryden F-15B FE model. These combined F-15B QS FE models were used as baseline models for parametric variations in F-15B QS connection stiffness for flutter sensitivity analyses.

A. Third Ground Vibration Test: Setup

The QS was fully extended and mounted horizontally on a 1.25-in. thick steel strongback fixture in the GAC structural lab, as shown in Fig. 20. The intermediate bulkhead and attachment ring of the QS were connected to the strongback in the same way as in the 1st GVT at NASA Dryden. One main difference between the 3rd GVT and the 1st GVT phase was the installation of the QS custom radome on the spike before the 3rd GVT was conducted.

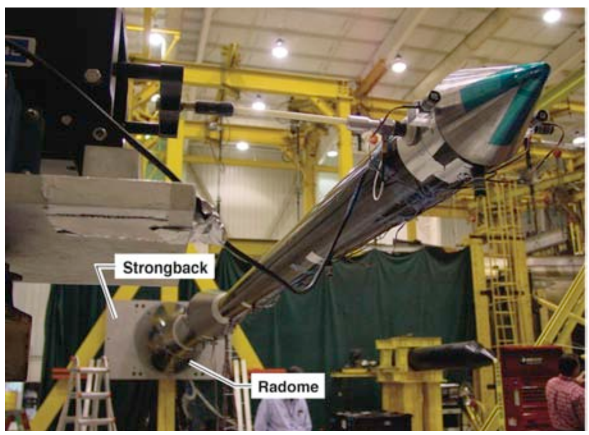

Figure 20. The QS horizontal strongback GVT configuration at Gulfstream Aerospace Corporation.

After the initial test data was analyzed, it was determined that the GAC strongback was not sufficiently massive to simulate a rigid boundary condition in the lateral direction. As a result, the QS 2nd lateral bending mode was coupling with the strongback lateral mode to produce two coupled lateral 2nd bending modes. To decipher the QS 2nd lateral bending mode, the QS test article was vertically mounted to the concrete floor. This test setup provided a very stiff and rigid boundary condition that did not couple with any of the QS modes of interest (see Fig. 21).

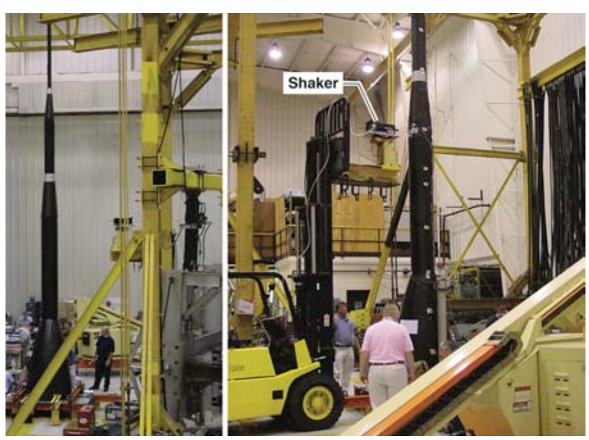

Figure 21. The QS vertical GVT configuration at Gulfstream Aerospace Corporation.

B. Third Ground Vibration Test: Instrumentation

For the 3rd GVT test configuration, 32 external accelerometers were used for the QS and the strongback (see Fig. 22). A majority of the accelerometers were on the QS test article in the vertical and lateral directions, but some were placed on the strongback to examine the behavior of the boundary conditions. When the QS was built, 48 internal accelerometers were installed for flight-testing. During the 3rd GVT phase the internal accelerometers were recorded and compared to the external accelerometers at approximately the same locations to verify that the flight accelerometers were functioning correctly and had correct calibration values.

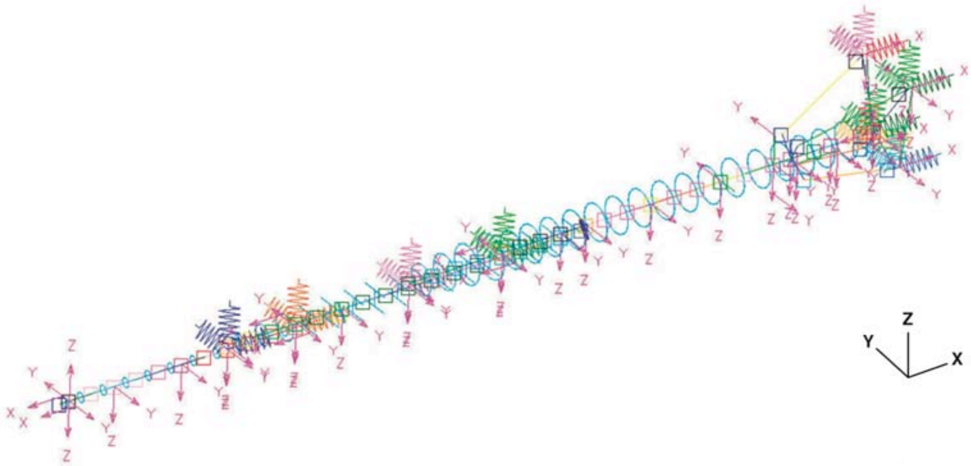

Figure 22. The mated QS with the F-15B accelerometer locations.

Originally, the shakers were oriented in the direction of known QS deflections (lateral and vertical) at the tip of the 4-in. segment to obtain the "cleanest" mode shapes for model correlation. Due to height restriction for the shaker stand configuration when the QS was rotated to the vertical orientation, the shaker excitation locations were relocated from the tip of the 4-in. segment to the tip of the 16-in. segment. The shaker was connected on the side and lower surface of the QS. The 16-in. segment lower excitation locations still excited all modes of interest. To position the shaker at the 16-in. segment of the QS, the GAC custom-built shaker stand was clamped to a forklift, as shown in Fig. 23.

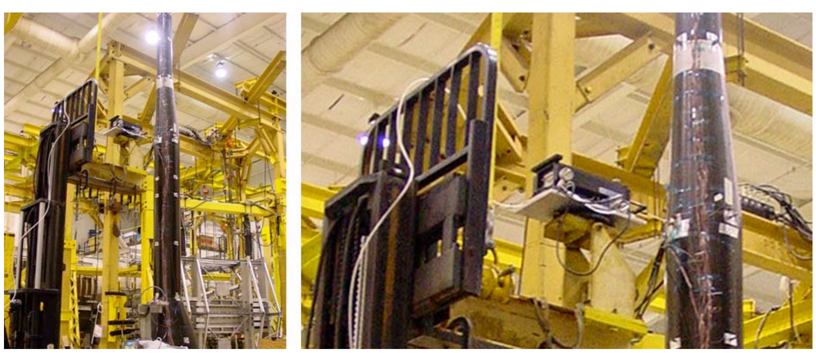

Figure 23. The shaker setup for the vertical strongback QS GVT.

C. Third Ground Vibration Test: Configurations and Results

For the 3rd QS GVT phase, several different test configurations (3-A to 3-G), shown in Table 3, were performed due to the strongback coupling with one of the QS modes in the horizontal test setup. All test configurations were conducted with the QS fully extended. Each shaker configuration was excited with either a burst random input at three different force levels or a sinusoidal sweep at several different input levels. A few impact tests were completed to locate the torsion mode and axial modes of the test article but a majority of the tests used burst random input and sine sweeps. A total of 38 test runs were completed with the QS attached to the strongback in the horizontal and vertical test configurations. Several of these data sets were curve fitted and compared.

Table 3. The Gulfstream Aerospace Corporation strongback QS GVT configurations.

Conf.	QS Orientation		Excitation Direction		Excitation Input		
	Vertical	Horizontal	Vertical	Lateral	Burst Random	Sine Sweep	Impact
3-A		X	X		X		
3-B		X		X	X		
3-C		X	X			X	
3-D		X		X		X	
3-E		X		X			X
3-F	X		X			X	
3-G	X			X		X	

Test configurations 3-F and 3-G were vertical and lateral excitations with the QS mounted in the vertical orientation. The lowest force level input data sets were curve fitted and the results were used to update and correlate the extended QS FE model (see Fig. 24). In the vertical mounted configuration the first two QS bending modes in each direction were clearly identified, therefore, resolving the strongback rigidity issue in the lateral direction. The 3rd GVT data from the horizontal and vertical QS mounting configurations were compared. The vertical orientation showed that the QS 1st lateral bending mode increased and the previously coupled strongback and QS 2nd lateral bending modes were decoupled. The extra stiffness provided by the QS radome and the geometry difference between the QS and the Mock QS suppressed the torsional mode that was seen with the Mock QS in the 1st GVT.

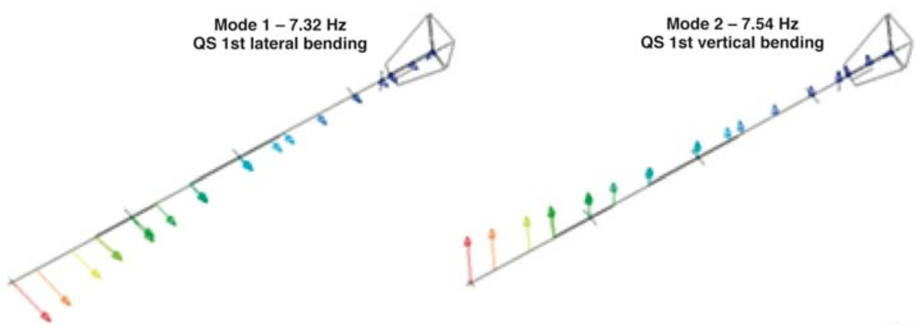

Figure 24. The mode shape of the strongback QS extended in vertical orientation.

V. Fourth Ground Vibration Test: Mated Quiet Spike™ with F-15B Airplane

The 4th GVT performed was with the QS mated to the F-15B airplane in the actual flight configuration. This last GVT phase was considered a mini-GVT because a minimal number of accelerometers were used which provided insufficient data to update the FE model. The objectives of this final GVT were to measure the primary frequencies of the extended QS mated to the F-15B airplane for validation of the connection spring and to measure the primary frequencies of the retracted QS mated to the F-15B airplane to verify that the FE model was correctly modeled. The final GVT data was also used to determine which flutter case was appropriate to select from the flutter sensitivity study for detailed analysis.

A. Fourth Ground Vibration Test: Setup

For the 4th GVT with the QS mounted to the F-15B airplane, three different aircraft boundary conditions were tested. First, the F-15B airplane was constrained and leveled on jacks with the same hardware as was used in the 2nd GVT. Second, the F-15B airplane was tested in a soft tire environment. Finally the F-15B airplane was installed on a NASA Dryden soft support system.

Prior to the 2nd GVT phase with the Mock QS mated to the F-15B, it was believed that to decouple and raise the aircraft modes away from the Mock QS modes of interest would require several aircraft constraints. The soft tire test data from the 2nd GVT showed the F-15B airplane and Mock QS modes were sufficiently decoupled; however, a direct comparison of the connection springs with the aircraft constraints was deemed required. Therefore, the identical constraining hardware used for the 2nd GVT was used for this configuration of the 4th GVT (see Fig. 25). Three vertical constraints were placed on the F-15B airplane: one on the aft centerline of the fuselage, one on each wingtip, and one on each horizontal stabilizer. Three symmetric lateral constraints were installed along the forward, middle and aft fuselage. The F-15B airplane was tested in the empty fuel configuration.

Figure 25. The GVT configuration of the mated QS with the F-15B airplane in constraints and on jacks.

The second aircraft boundary condition tested was with the F-15B airplane supported on soft tires. The tires were deflated to the lowest allowable pressures to try to simulate as close as possible a soft boundary condition with minimal setup requirements. The GVT testing on soft tires was performed with the F-15B airplane fully fueled and with the QS extended, retracted, and in an intermediate position.

Lastly, the F-15B airplane was installed onto a NASA Dryden developed soft support system that simulates a free-flight configuration and acts to isolate the rigid-body modes from the airplane's elastic-structural modes. The 60,000-lb-capacity soft support system was installed at each of the three F-15B jacking locations. Each soft support (see Fig. 26) consists of a canister with a nitrogen-filled bladder to isolate the aircraft from the ground, an automated mechanical lifting jack, and a three-axis load cell to monitor the aircraft weight and any load shift in any of the three axes. Each soft support is rated for a vertical load of 20,000 lb and a side load of 1400 lb. The GVT was carried out with the F-15B airplane fully fueled, on the soft support system, and with the QS extended, retracted, and in an intermediate position. The landing gear remained down while the F-15B airplane was on soft supports, with each tire having a small clearance from the ground, as shown in Fig. 27.

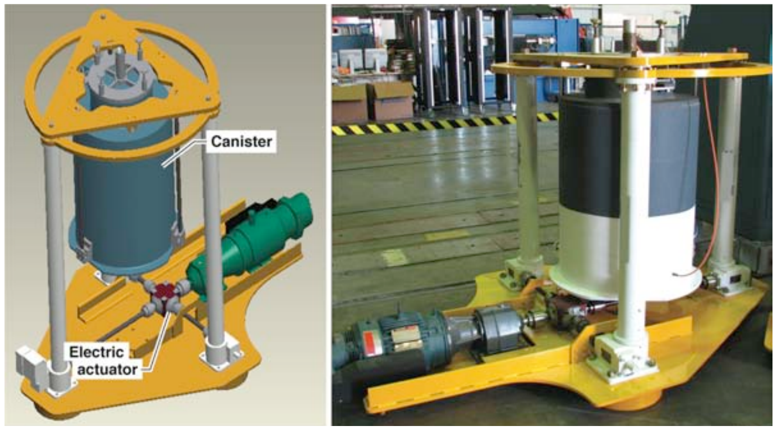

Figure 26. The NASA Dryden self-jacking soft support system.

Figure 27. The GVT configuration of the mated QS with the F-15B airplane on soft supports.

B. Fourth Ground Vibration Test: Instrumentation

The 4th GVT configuration had a minimal number of external accelerometers, (total of 28) between the QS and the F-15B airplane, since the objective of this test was to verify the modal results of the FE model. Figure 28 shows a comparison of the accelerometer distribution used during the 2nd GVT for model updating compared with the minimal accelerometers used during the 4th GVT for model verification. Twelve accelerometers were placed on the upper surface of the QS in the vertical and lateral directions to capture the vertical and lateral bending modes. The remaining 16 accelerometers were placed on the F-15B airplane to monitor the airplane movement and assist in the data reduction.

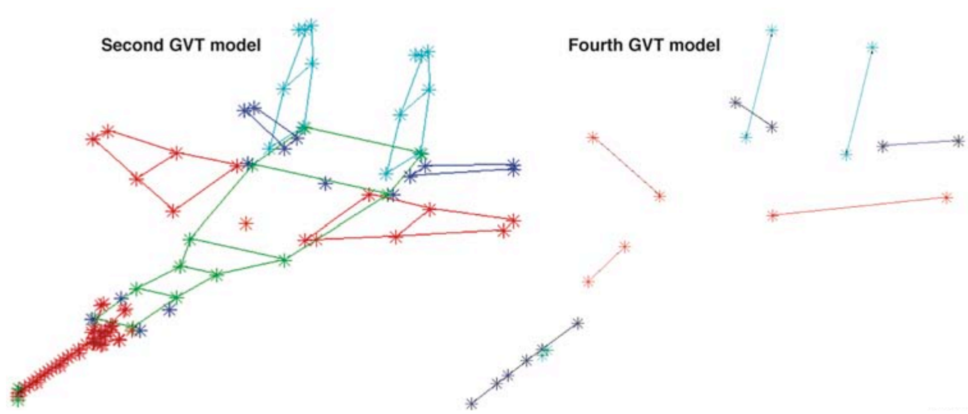

Figure 28. Comparison of the Mated Mock QS and the mated QS accelerometer locations.

The shakers were connected to the QS at the same location on the aft (16-in.) segment tip as in the 3rd GVT with the QS vertically mounted. Burst random excitation was applied vertically on the center of the lower surface of the spike and laterally on the left surface of the spike at the forward portion of the aft segment (see Fig. 29).

Figure 29. The shaker setup for the GVT of the mated QS with the F-15B airplane.

C. Fourth Ground Vibration Test: Configurations and Results

The 4th GVT phase included many different test configurations (4-A to 4-N) as shown in Table 4. The tests were performed using three different aircraft boundary conditions and with the QS in the retracted, extended, and intermediate positions. The F-15B airplane was in an empty fuel configuration for the constraint tests and fully fueled for the soft tire and soft support tests. Each shaker configuration was excited with a burst random input at three different force levels and all configurations were tested with a zero clevis axial load. A total of 46 test runs were completed with the QS attached to the F-15B airplane in the flight configuration. Several of these data sets were curve fitted and compared.

Table 4. Mated QS with F-15B GVT Configurations.

Conf.	Excitation Direction		QS Position			Boundary Condition				F-15B Fuel	
	Vert.	Lat.	Retr.	Ext.	Int.	Constr.	On Jacks	On Soft Tires	On Soft Supports	Empty	Full
4-A		X		X		X	X			X	
4-B	X			X		X	X			X	
4-C		X		X				X			X
4-D	X			X				X			X
4-E		X	X					X			X
4-F	X		X					X			X
4-G		X			X			X			X
4-H	X				X			X			X
4-I		X		X					X		X
4-J	X			X					X		X
4-K		X	X						X		X
4-L	X		X						X		X
4-M		X			X				X		X
4-N	X				X				X		X

Test configurations 4-A and 4-B in the F-15B airplane constrained boundary condition were used to confirm the connection stiffness between the F-15B airplane radar bulkhead and the QS. Mode shapes of the extended QS with the F-15B airplane constrained and on jacks can be seen in Fig. 30. These frequencies were compared with the analytical correlated constrained F-15B QS FE model, which contained the connection springs measured in the 2nd GVT.

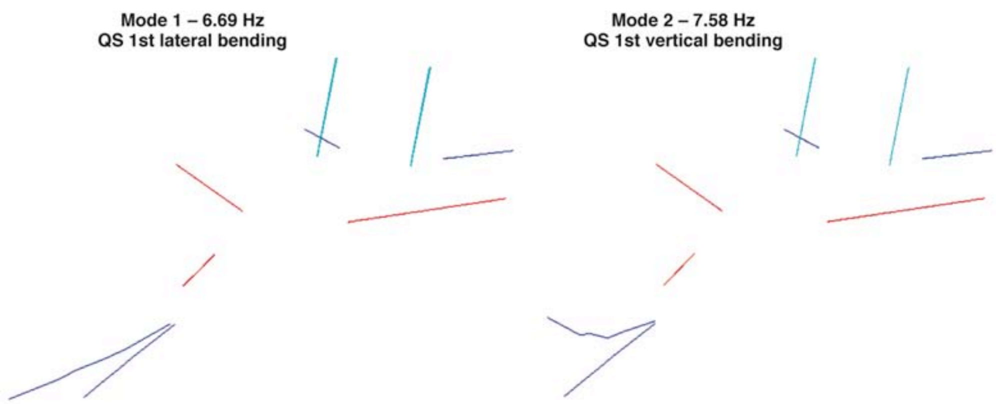

Figure 30. The mode shapes of the mated QS extended with the F-15B airplane constrained and on jacks.

Test configurations 4-I to 4-L, with the F-15B airplane on the soft support system, were used to compare the analytical results of the combined QS F-15B FE model with free-free boundary conditions. Mode shapes of the extended QS and retracted QS can be seen in Figs. 31 and 32, respectively.

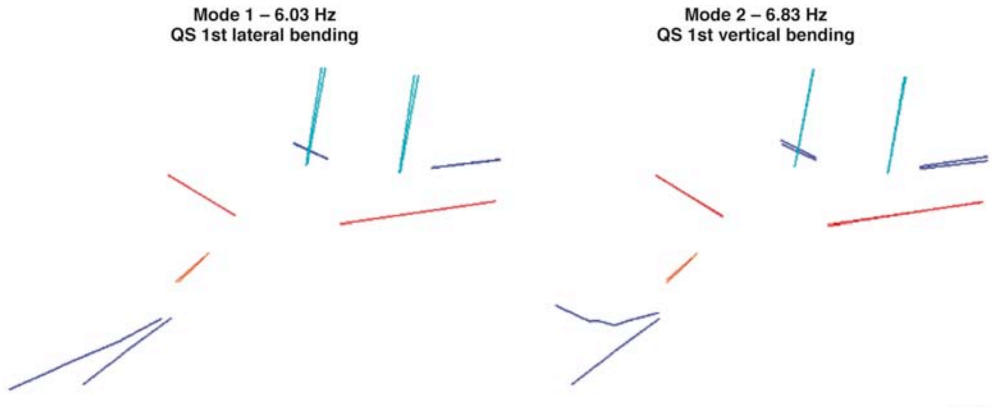

Figure 31. The mode shapes of the Mated QS extended with the F-15B airplane on soft supports.

Figure 32. The mode shapes of the Mated QS retracted with the F-15B airplane on soft supports.

The final F-15B QS FE model consisted of the correlated QS FE model from the 3rd GVT, the updated connection stiffness from the 2nd GVT, and the NASA F-15B FE model. A modal analysis with free-free boundary conditions was run with the combined F-15B QS FE model. The soft support data from the 4th GVT phase proved that the connection stiffness between the F-15B airplane radar bulkhead and the QS was correctly modeled in the combined free-free FE model, and also showed excellent F-15B QS test-to-model frequency correlation (within 3.5 percent), see Table 5. Therefore, no model updating was necessary at the end of the 4th GVT phase, which was the original intent of the entire Quiet Spike™ ground vibration test build-up approach. The free-free analytical F-15B QS FE model was used for the flutter sensitivity study. The final GVT test data was also used to determine which flutter case was appropriate to select from the flutter sensitivity study.

Table 5. The F-15B QS finite element model and 4th GVT comparison.

Mode Shape Description	F-15B QS FE Model (Free-Free) Freq. (Hz)	4th GVT (Soft Support) Freq. (Hz)	FE Model vs. 4th GVT % Error
QS Extended			
QS 1st Lateral Bending	5.87	6.03	-2.73%
QS 1st Vertical Bending	6.70	6.83	-1.94%
QS Retracted			
QS 1st Lateral Bending	7.00	6.77	3.29%
QS 1st Vertical Bending	8.26	7.97	3.51%

VI. Conclusions

Updating and correlating the Mock Quiet Spike™ and Quiet Spike™ finite element models throughout the incremental ground vibration test build-up approach proved to be a successful method for this program. The final ground vibration test data confirmed the connection stiffness was modeled correctly and showed excellent test-to-model comparisons, therefore no further model updating was required. The four ground vibration tests required more work than if a single "traditional" ground vibration test in the final flight configuration had been performed, but the build-up approach allowed the Quiet Spike™ program to remain on schedule for flight.

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References

[1]Freund, D., Simmons III, F., Spivey, N. D., and Schuster, L., "Quiet Spike™ Prototype Flight Test Results," AIAA-2007-1778 (to be published).

[2]Howe, D. C., "Improved Sonic Boom Minimization with Extendable Nose Spike," AIAA-2005-1014, Jan. 2005.

[3]Simmons III, F., and Freund, D., "Morphing Concept for Quiet Supersonic Jet Boom Mitigation," AIAA-2005-1015, Jan. 2005.

[4]Simmons III, F., and Freund, D., "Wing Morphing for Quiet Supersonic Jet Performance – Variable Geometry Design Challenges for Business Jet Utilization," AIAA-2005-1017, Jan. 2005.

[5]Simmons III, F., Freund, D., Spivey, N. D., and Schuster, L., "Quiet Spike™: The Design and Validation of an Extendable Nose Boom Prototype," AIAA-2007-1774 (to be published).

[6]Herrera, C. Y., and Pak, C., "Build-up Approach to Updating the Mock Quiet Spike™ Beam Model," AIAA-2007-1776 (to be published).