4.0 Test Procedure and Setup

The Test Procedure and Setup section is divided into eight categories: sensor calibration, preliminary equipment setup, equipment changes, excitation frequency determination, node layout, Maxwell’s Reciprocity Theorem test, final ground vibration test, and I-DEAS procedure. These categories provide a step-by-step setup and procedure method for the testing and analysis performed in the GVT.

4.1 Sensor Calibration
Impact-hammer ratio calibration was performed in order to convert dimensionless frequency response measurements from the load cell and multi-axial accelerometer into the physical engineering ratio of inertance (acceleration/force). The ratio calibration was conducted according to the ratio calibration theory presented in section 2.8 of the Theory section. This section describes the impact-hammer test setup, configuration of the DSA (Dynamic Signal Analyzer), and storage of the ratio-calibration data.

4.1.1 Impact-Hammer Setup
A hanging weight was suspended like a pendulum from a metal support rod, and a steel-hardened impact mass and the multi-axial accelerometer were attached to opposite ends of the hanging weight. The combined mass of the hanging-weight, accelerometer, and impact-mass was 841.8 grams. The load cell was connected with a BNC cable to Channel 1 of the DSA and physically mounted to the impact hammer. The accelerometer output was connected to the DSA through input Channel 2. The three axes of the accelerometer were calibrated separately by aligning the accelerometer axis of interest in the axial direction of the hanging weight. A photograph of the ratio calibration equipment and the actual ratio calibration test is shown in Fig. 22.

![Figure 22. Ratio Calibration Equipment and Test](image-url)
4.1.2 HP 3657A Ratio Calibration Setup
In the Hardware Setup Mode of the Front End Page, two channels were selected to perform the ratio calibration: Channel 1 for the load cell and Channel 2 for the accelerometer. The ranges of the load cell and accelerometer were set to their peak-sensitivity values, 5V and 2V, respectively. Both channels were set to ac coupling and the ICP mode was selected to provide the required 4 mA current to drive the instruments. In the Measurement Mode, the MeasParam menu was used to set a frequency span of 1600 Hz. The Nyquist Criterion was met by using 3200 frequency lines for the frequency resolution. The MeasParam menu was also used to select the options of a Uniform Time-Domain Window and Stable Averaging for the data analysis. In the Source menu of the Hardware Setup page, the DSA was configured to trigger only when the hammer provided an impact force equivalent to 10% of the load-cell voltage range, 5 V.

4.1.3 Data Acquisition and Storage
The frequency response for each axis of the accelerometer was stored for future calculation of the calibration ratios. The data was stored in the directory Analyzer/Data/3MAAP_Data on the Pentium computer located in room 202 of Woolrich Laboratories.

4.2 Preliminary Equipment Setup
Several equipment changes were made to the initial setup in order to reduce data errors. This section provides a general description of the setups, a detailed description of the DSA configuration, and a detailed description of the equipment changes that account for the current test configuration. The reasons behind the setup changes are further explained in the Results section.

4.2.1 Initial GVT Configuration
The initial configuration for the GVT is illustrated in Fig. 23.
The electro-magnetic shaker was positioned under the left wing, approximately 2 feet away from the wingtip. The accelerometer was positioned on top of the wing, close to the shaker attachment location. A 3 ft. flexure, with stingers attached on both ends, was mounted to the shaker. The load cell was connected to the suction plate and the combination was connected to the top of the flexure fixture (Fig. 24).
The DSA source output was connected to the shaker via the power amplifier. The amplifier was turned on 15 minutes prior to testing in order to allow all the vacuum tubes to warm up. In order to apply a dynamic load to the Star-Lite, the selector switch on the front panel of the amplifier was set to position T, and the Gain knob on the amplifier backpanel was used to set the shaker vibration amplitude. The load cell and accelerometer signals were connected to the input channels of the DSA, and the pump hose was connected to the suction plate in order to form a vacuum between the plate and wing surface (Fig. 25).

The Star-Lite landing gear were constrained with the inner tube supports, as described in section 3.2.2, in order to isolate the rigid body modes from the flexible modes. In addition, the control sticks were locked into position with the constraints shown in Fig. 26, and pieces of rubber gasket were placed in the control-surface gaps of the vertical elevator in order to prevent nonlinear control-surface vibration (Fig. 27).
4.2.2 Initial HP 3657A Setup

Five input channels were selected in the Front End menu of the Hardware page in order to perform the preliminary tests on the Star-Lite. Channel 1 was selected for the load cell response and Channels 2, 3 and 4 were selected for X, Y, and Z accelerometer responses, respectively. Channel 5 was used to monitor the input signal generated by the DSA. The DSA backpanel connections are shown below (Fig. 28).
The instantaneous time response of the load cell and accelerometer were observed before any measurements were recorded. The peak-to-peak value of the data was input into the DSA ranges for the transducers in order to achieve amplitude half-ranging of the signals; half-ranging is described in section 2.6.3 of Theory. Channel 5 was set to the Voltage Mode since the source is a standard voltage input, and the other four channels were set to ICP mode in order to send a 4 mA current to power the load cell and accelerometer. All channels were set to ac coupling. In the Source menu of the Hardware Setup page, the analyzer was configured to generate a transient, burst random signal. The length of the signal was chosen to be 30% of the time record so that the responses would decay in the sample period, and the output voltage of the source was set to $1 \text{ V}_{\text{rms}}$ in order to drive the MB Power Amplifier at full output potential. In the Measurement mode, the MeasParam menu was used to incorporate a Uniform time-domain window and Stable averaging to the data. The DSA Frequency Span for testing was set at a range of 10 Hz to 1600 Hz, and the number of Frequency Lines was set to at least twice the highest frequency.

### 4.3 Equipment Changes

This section gives a point-by-point progression of the different equipment changes made in the GVT analysis and why those changes were kept or discarded. The equipment changes end with the final GVT configuration. A more thorough explanation of the changes and their effect on the response of the Star-Lite is provided by the Results section and coinciding data in Appendix D.
Analysis of the data collected from the initial GVT setup (Fig. 23) showed flaws in the equipment setup. Subsequent attempts to resolve the problems led to equipment changes. The first step taken toward proper equipment configuration was the inclusion of a 4-channel Tektronix 561A oscilloscope into the initial setup (Fig. 19). The oscilloscope was connected to the DSA in order to monitor the real time signals coming from the load cell and accelerometer.

Continued analysis revealed the presence of signal conditioning and ground loops feeding energy back into the system. The oscilloscope was determined to cause the conditioning and was removed from the setup. The ground loops were removed by connecting the amplifier and DSA to the same power outlet so they would have a common group.

Additional GVT testing still showed data errors due to the equipment. The next step taken was to test a different shaker. The new instrument proved to be faulty and was discarded. Troubleshooting then shifted toward the accelerometer mounting device, which was wax. A 2-channel Kikusui DSS 6520A Digital Storage Oscilloscope (Fig. 20) was used to identify the wax effects on the accelerometer signal. The oscilloscope readouts revealed that the wax had to be significantly depressed in order to produce good accelerometer measurements from the structure. During the wax analysis, faulty BNC cables were discovered to be additional causes of data error, and the built-in accelerometer cables linking the sensor to the DSA were also faulty. The connections were cleaned with an electronic-component cleaner spray and new BNC cables were installed. Additionally, the accelerometer was repaired, the 2-channel oscilloscope was removed from the setup and testing of the mounting device continued.

Testing resumed again but the 3 ft. flexure started vibrating laterally so a shorter 1.5 ft. fixture was incorporated into the test setup. In addition, a thinner, vinyl pump hose was used to replace the initial rubber tube. Verification tests revealed that the new flexure did not vibrate laterally so the vibration tests were resumed. Subsequent data analysis revealed that additional problems resulted from inaccurate range settings on the DSA for the accelerometer and load cell. Additional noise was also coming from nonlinear vibrations of the control surfaces. To solve these problems, more rubber gaskets were used to constrain the control surfaces, and the DSA was reconfigured to half-amplitude ranging.

Analysis of the accelerometer instantaneous-time responses revealed the presence of low frequency oscillations. In order to rule out the possibility of flexure induced oscillations,
the 1.5 ft. flexure was replaced with the 3 ft. flexure. Combinations of lead shot fingers attached to the flexure (Fig. 29), together with added weight placed on the shaker were used in an attempt to damp out the low frequency oscillations.

![Figure 29. Individual Lead Shot Fingers and 3 Ft. Flexure with Attached Finger](image)

The flexure adjustments provided no major improvements in data quality from the prior tests with the short flexure. Additionally, the 3 ft. flexure produced an audible buzz during testing that was representative of the previously encountered lateral oscillation problem. At this point, the 1.5 ft. flexure was placed back into excitation setup and remained in the test setup throughout the GVT data acquisition.

The troubleshooting for the low frequency oscillations shifted towards the test room conditions and possible low frequency vibration of the structure. An air duct directly above the aircraft was observed to be blowing air towards the Star-Lite so the vent was sealed (Fig. 30). In addition, the canopy of the aircraft was taped to the fuselage to prevent it from vibrating (Fig. 30). These two adjustments significantly reduced the low frequency oscillations for a portion of the testing procedure; however, the oscillations continued to appear sporadically and their cause was determined to be due to a buzz in the electrical components. Ultimately, the low frequency oscillations were disregarded; the reasoning behind this decision is presented in the Results section.
The next step taken towards improving data quality was to replace the 50 lb. shaker with a 35 lb. that was assembled by 3MAAP. The new shaker allowed for an increase in the amplifier gain. The higher gain increased the amplitude of vibration without overloading the load cell and accelerometer.

The inclusion of the new shaker marked the end of the equipment changes made to the GVT setup. The only other modifications to the GVT involved the DSA configuration, which is discussed in a later section. The final setup configuration is shown in (Fig. 31). At this point, 3MAAP proceeded to perform tests involving the excitation frequency range, node layout, Maxwell’s Reciprocity Theorem, and final GVT data acquisition.
4.4 Excitation Frequency Determination

The determination of the excitation frequency range was a simple task. GVT data was initially recorded over a 0 Hz to 1600 Hz frequency range to determine the significant natural frequencies in the Star-Lite. A lack of frequency resolution in the 0 Hz to 100 Hz range required smaller frequency bandwidths to be tested in order to determine the significant natural frequencies. Tests were performed over a 0 Hz to 200 Hz range and the most significant frequencies appeared over the 0 Hz to 50 Hz range. A test frequency range of 0 Hz to 100 Hz was chosen in order to obtain a larger range of modes than were determined in the 1989 GVT [2]. The 1989 GVT had a frequency range of 0 Hz to 50 Hz.
4.5 Node Layout
The process to determine and assemble the measurement point layout is combined into two categories: they are broken into a wing/vertical-stabilizer category and a fuselage/vertical-tail category. The nodes were determined by following the method outlined in section 2.4.3 of Theory. The process of determining the required node spacing is presented in the Results section. The remainder of this section discusses the method used to assign the coordinate locations of each node on the aircraft. For a detailed description of node numbers and their coordinate locations in reference to the origin on the Star-Lite, refer to the node position data at the end of Appendix E. The position of the origin was defined on the underside of the aircraft at the imaginary intersection of the left-wing, leading-edge spar with the aircraft longitudinal axis of symmetry.

4.5.1 Wing/Vertical-Stabilizer Node Layout
The grid layout for the FR measurements had to be precisely mapped on the surface of the aircraft in order to create an accurate computer model of the Star-Lite. Node spacing was accurately measured by 3MAAP through the use of squares, levels, and plumb bobs (Fig. 32).

The process for determining the node layout was initiated by finding the locations of the wing ribs and spar. As Fig. 33 shows, the ribs were located along the wing by using an impact hammer; they were then marked with red wax. Next, the leading edge of each wing was determined and labeled through the use of a plumb bob (Fig. 33).
The span-wise spacing between nodes was selected by placing nodes over the leading edge spar at junctions between the ribs and spar (Fig. 34). The control surface nodes were placed in line with the ribs but 1 inch away from their fore and aft edges (Fig. 34). The aft row of three wing nodes was placed 1 inch away from the trailing edge of the wing (Fig. 34).
was always under 10 in. The three chord-wise nodes were needed to provide enough points to accurately model the twisting of the wing and control surfaces.

The procedure used to determine the node layout on the wings was also used to determine the node layout on the vertical stabilizers. The vertical stabilizers do not have ribs or spars but the method used to discretize the wing was already established and was easily transferred to the vertical stabilizers. The first span-wise row of nodes on the vertical stabilizer were placed 4 in. aft of the stabilizer leading edge. The second span-wise row of nodes were placed 8 inches aft of the first row. Finally, the two span-wise rows on the elevators were placed one inch apart from fore and aft edge of the control surface (Fig. 35). Figure 35 also shows the grid layout for the rudder.

![Figure 35. Tail Node Layout](image)

**4.5.2 Fuselage/Vertical-Tail node layout**

Figure 35 shows the location of the vertical tail nodes. A quadrilateral grid of node points was laid on the rudder at longitudinal locations of 1 in. fore and aft of the control surface edges. The vertical tail was modeled using a triangular grid with 8 in. and 4 in. spacing between nodes (Fig. 36).
The nodes on the fuselage were placed along the top, bottom, and sides of the fuselage (Fig. 37). This arrangement was chosen in order to obtain a clear description of fuselage bending behavior.

The nodes on the top and bottom of the fuselage were placed along the aircraft’s longitudinal axis of symmetry (the line from tail to nose). The set of side nodes were placed along the fuselage’s sides at the outermost point from the centerline of the structure; the outer-most position was determined through measurements with squares and levels (Fig. 32).
4.6 Maxwell’s Reciprocity Theorem Test
Maxwell’s Reciprocity Theorem was tested on the Star-Lite by performing the procedure outlined and pictured in section 2.5 of Theory and Fig. 6, respectively. The first FR measurement was taken with the shaker attached to the underside of the left wing, directly below node 13, and the accelerometer attached on the right wing at node 87. The second FR measurement involved placing the shaker under the right wing directly below node 87, and the accelerometer at node 13 on the left wing. After the test was completed, the shaker was returned to its original position under the left wing at node 13.

4.7 Final Ground Vibration Test
4.7.1 Final HP 3657A Setup
Four input channels were selected in the Front End menu of the Hardware page in order to perform the final GVT on the Star-Lite. Channel 1 was selected for the load-cell response and Channels 2, 3 and 4 were selected for the X, Y, and Z accelerometer responses, respectively; the DSA backpanel connections are shown in Fig. 28. The DSA was configured with two instrument states (Calibration State and Final State) that were required for the final test phase.

4.7.1.1 Calibration State - In the Hardware Setup Page of the DSA, the length of the burst-random source signal was set to 75% of the time record. All the channels were set to ac Coupling and ICP Mode. The test frequency range was set at 0 Hz to 100 Hz. The measurement page of the analyzer was configured to display the instantaneous-time response of the Star-Lite in all three x, y and z directions (Channels 2,3, and 4, respectively, in Fig. 38). The MeasParam menu was selected in order to set the frequency resolution to 1600 lines, the Averaging to Stable, and the Window to Uniform.

Figure 38. Time Domain Display of Accelerometer Readings
4.7.1.2 Final State - In the Hardware Setup Page of the DSA, the length of the burst-random source signal was set to 75% of the time record. All the channels were set to ac Coupling and ICP Mode, and the test frequency range was set at 0 Hz to 100 Hz. The calibration ratios calculated from the ratio calibration of the sensors were integrated into the DSA through the Eng.Unit menu of the Hardware Setup page (Fig. 39). The MeasParam menu in Measurement page was used to set the frequency resolution to 1600 lines, the Window to Uniform, the Averaging to Stable, and the number of averages to 16.

![Integration of Calibration Ratios into the HP 3657A Dynamic Signal Analyzer](image)

4.7.2 Test Procedure

The testing of the Star-Lite was conducted by gathering results from the aircraft in the following order: wings, horizontal stabilizer, fuselage, and vertical tail. The test configuration for the final GVT tests is shown in Fig. 31. In order to perform each test, the accelerometer was placed at a node and the Calibration State was loaded into the DSA. The calibration was performed in order to determine the amplitudes of the accelerometer and load cell readings during the vibration of the aircraft. These values were used to provide amplitude half-ranging of the data. After the calibration was complete, the DSA was reconfigured by loading the Final State (Fig. 39).

The peak-to-peak values of the data observed during the calibration run were input into the DSA ranges for the transducers. The measurement page of the analyzer was configured to display Frequency Response and Coherence, and the testing resumed. After the 16
averages were taken, the data was saved in the analyzer’s data folder. The accelerometer was moved to a different node and new measurements were taken. The procedure was repeated to measure the response at all the nodes on the Star-Lite.

The GVT data procedure for the fuselage and vertical tail required some additional steps. In order to keep the accelerometer parallel to the Star-Lite’s reference axis, an aluminum block was used to mount the accelerometer over the curved and inclined surfaces (Fig. 40).

![Accelerometer and Mounting Block](image)

**Figure 40. Accelerometer and Mounting Block**

The accelerometer had to be rotated while measuring the responses on the side of the fuselage and vertical tail. The rotation caused the accelerometer axes to switch positions so the cables connecting the accelerometer to the DSA were switched in order to keep Channels 2, 3, and 4 coincident with the X, Y and Z global reference directions, respectively. Refer to Fig. 41 and Table 2 for an explanation of the accelerometer orientation at different airplane locations, as well as the procedure for swapping DSA cables in order to maintain the same directions for Channels 2, 3, and 4. In Table 2, cables connecting the accelerometer axes to the DSA Channels are referred to by the associated axis names (e.g. the cable connecting the accelerometer’s x-axis to the DSA is referred to as Cable x).
Figure 41  Accelerometer Orientation Relative to the Star-Lite Reference Coordinate Axis

Table 2. Description of Accelerometer-Cable/DSA-Channel Connection

<table>
<thead>
<tr>
<th>Airplane Location</th>
<th>Accel. direction (lowercase) in relation to Airplane’s axis (uppercase)</th>
<th>Switching operations (*)</th>
</tr>
</thead>
</table>
| Wings & Stabilizer                 | x → - X  
y → Y  
z → Z                                             | Cable x → Channel 2  
Cable y → Channel 3  
Cable z → Channel 4 |
| Right Side Fuselage                | x → - Y  
y → - X  
z → - Z                                        | Cable x → Channel 3  
Cable y → Channel 2  
Cable z → Channel 4 |
| Left Side Fuselage & Vertical Tail | x → Y  
y → X  
z → - Z                                      | Cable x → Channel 3  
Cable y → Channel 2  
Cable z → Channel 4 |
| Bottom Fuselage                    | x → - X  
y → - Y  
z → Z                                          | Cable x → Channel 2  
Cable y → Channel 3  
Cable z → Channel 4 |

(*) The calibration ratios in the DSA Channels were switched accordingly
4.7.3 Data Transfer from the HP 3657A DSA to I-DEAS
Data analysis and modal animation were performed by using I-DEAS Modal Plus software located installed on a Unix-based server, Oberon, in the Aerospace Engineering Learning Resource Center. The data recorded during testing was stored in the HP data folder located on the Pentium PC located in the Aeroelasticity Lab (WRW 202) at the University of Texas at Austin. Since the data and analysis software were located on different computers with independent platforms, the data files had to be transferred through a common data format. The first step in transferring the data was to transform the data files created by the DSA into a format compatible with I-DEAS. The Utilities menu on the DSA Measurement page provided the option “SDF → SD58”. This utility program was used to convert the DSA data files, [filename].dat, into a format compatible with I-DEAS. Once all the data files were converted to SD58, they were imported into I-DEAS via FTP. In order to import the files into I-DEAS, the filenames had to named [filename]_frf.unv.

4.8 I-DEAS Procedure

4.8.1 I-DEAS Model Preparation Task
The Model Preparation Task (Fig. 42) within the I-DEAS Test application was used to generate a computer model of the Star-Lite according to the procedures in [4]. The model was assembled by using the x, y, and z coordinates that corresponded to the discrete measurement points on the Star-Lite. The model consisted of 248 nodes, displayed as an asterisk (*) in the I-DEAS design space. The nodes were connected with elements across the wings, tail, and fuselage in order to give the model the characteristic shape shown in Fig. 37. The elements of the fuselage were connected in a diamond-shape fashion in order to represent the hollow fuselage of the Star-Lite.

Figure 42. I-DEAS Model Preparation Task
4.8.2 I-DEAS Modal Task

The I-DEAS Modal Task (Fig 43) provided estimations of the modal parameters from the GVT of the Star-Lite. The data was saved by the HP DSA in the Dataset 58 format which can be imported directly into I-DEAS. Once the data was imported, each FR was linked to the associated coordinates. Each set of data had the same reference excitation location corresponding to the shaker input at node 13. In I-DEAS, this position is indicated as 13Z-.

A normal MIF (Mode Indicator Function) was generated within I-DEAS for the data at all 248 nodes by following the procedures outlined in [4]. The polyreference time-domain technique was selected, and the valleys of the MIF were searched in order to create a parameter table of the natural frequencies, modal damping, and MCF (Modal Confidence Factor). The threshold and tolerance values were selected to filter out the valleys that were insignificant.

A matrix of the poles was generated with the build matrix function key after the search of the MIF valleys. The size of the matrix was set to the square of the number of parameters from the parameter table. Next, a stability diagram of the poles and frequencies was produced so that the poles of the frequency response data could be manually chosen. The poles were selected on the basis of stability and the MCF factor. Once the poles were selected, the polyreference frequency-domain technique was chosen to calculate the mode shapes, MAC (Modal Assurance Criterion), and the residues. Additional information on this process is available in [4].

Figure 43. I-DEAS Modal Task
4.8.3 I-DEAS Post Processing Task
The I-DEAS Post Processing Task (Fig 44) provided a modal animation of the Star-Lite after the modal parameters were determined. In order to display the deformation, the shape files were first loaded into the active memory by using the Results option. Next the Display Results option was used to provide a static display of the selected mode shape. Finally, the Animation option provided a continuous animation of the selected mode shape. For further information see [4].

Figure 44. I-DEAS Post Processing Task