CHAPTER SIX
ESDM EVALUATION: EXPERIMENTAL METHOD

The ability of ESDM to reconstruct surface velocity fields with large in-plane and small out-of-plane components was evaluated. Therefore, an experimental method was developed which permitted such an evaluation. This chapter presents the experimental method, including experimental approach and procedure, which enabled such an evaluation. Initially discussed are several experimental matters which required consideration before the experimental approach was developed. Subsequently, the experimental approach, essentially an overall framework for the experimental procedure, is established. Last, the actual experimental procedure is described.

Preliminary Considerations

Several experimental matters, including test structure motion, test structure excitation, an appropriate scan surface and scan point distribution, an independent ESDM evaluation standard and data acquisition, were considered before the experimental approach was established. This section discusses each matter considered.

First test structure motion was considered. Surface motion with large in-plane and small out-of-plane velocity components was required. Therefore, with guidance from Mitchell [57], the motion illustrated by Fig. 48 was specified. Large in-plane motion in the *x*-direction and small out-of-plane motion in the *z*-direction was specified; specifically, five percent *z*-direction motion relative to *x*-direction motion was stipulated. As required, such motion induced large in-plane and small out-of-plane velocity components on surfaces with normals aligned with the *z*-direction.

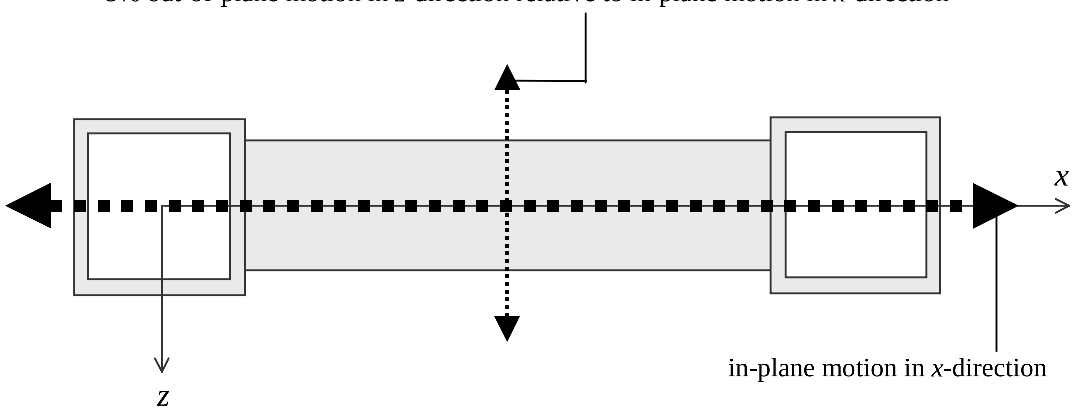

Figure 48. Plan view of specified test structure motion

Second, test structure excitation was considered. The excitation source selected was a shaker and stinger combination. An analysis was conducted to determine an appropriate stinger length and diameter which ensured the shaker did not excite any stinger longitudinal or transverse bending modes. Ultimately, a 1.5 in. (3.8 cm) long and 0.041 in. (1.0 mm) diameter steel stinger was selected.

The excitation location is indicated in Fig. 49. The excitation direction is also indicated in Fig. 49; it was perpendicular to the *y*-axis and oriented 10° from the *x*-axis. The excitation location and direction assured that 1) large *x*-direction motion and small *z*-direction motion was generated with minimal motion in other directions and 2) the excitation was directed through a point very near the geometric center point of the top brace thereby minimizing any third mode effects. A small brass boss coupled the shaker/stinger combination and test structure together. This ensured the excitation was directed in the specified direction. Cyanoacrylate type adhesive cement firmly attached the boss to the structure.

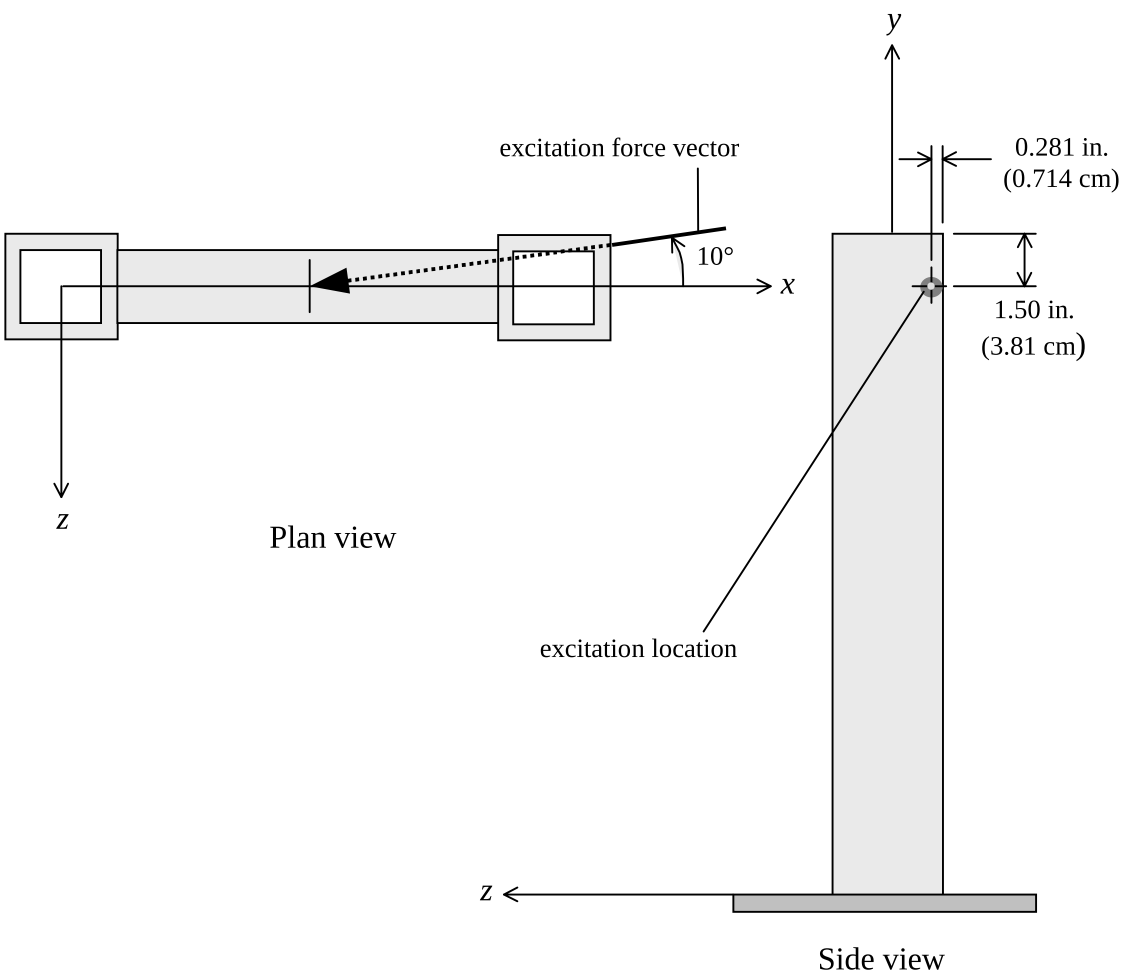

Figure 49. Test structure excitation location and direction

After the excitation direction and location were specified, the excitation frequency was selected. The test structure was excited by the arrangement previously described and accelerometers were placed near the top of one of the test structure columns. The accelerometers measured motion in the *x*- and *z*-directions. The excitation frequency was then varied between first and second modes, that is between 103 Hz and 176 Hz, until five percent *z*-direction motion relative to *x*-direction motion was indicated by the accelerometer. Such motion was achieved at 144 Hz; therefore, the excitation frequency selected was 144 Hz.

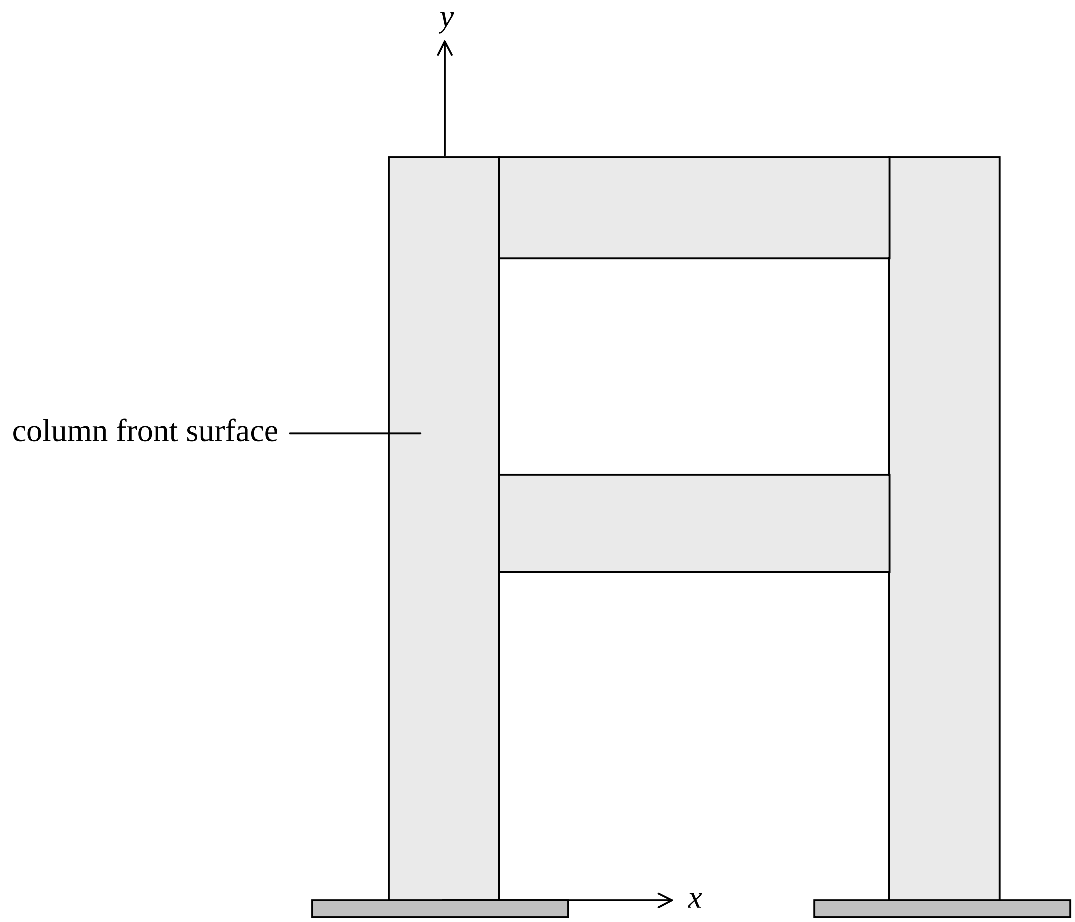

Figure 50. Scan surface selected

Third, an appropriate scan surface was considered. Figure 50 indicates the scan surface ultimately selected; it covers one entire column face with a surface normal oriented in the *z*-direction and is, henceforth, referred to as the column front surface. The column front surface was selected since, when the test structure motion indicated by Fig. 49 was generated, LDV scans over this surface yielded ESDM results with large in-plane and small out-of-plane velocity components. Such results were required for ESDM evaluation.

After the scan surface was selected, its scan point distribution was specified. However, before this occurred, a finite element mesh was constructed. Recall that velocity field reconstruction by ESDM requires a finite element mesh that describes the scan surface geometry; therefore, a finite element mesh of the column front surface was specified. The mesh was three elements wide and twenty-four elements high, contained seventy-two quadrilateral elements and modeled surfaces 2.5 in. (6.3 cm) wide[16] and 24.0 in. (61.0 cm) high; thus, the element density was approximately one element per square inch (6 cm^2).

The scan point distribution was dependent upon the finite element mesh size. Accurate velocity field reconstruction required at least three scan points per element. The mesh was three elements wide and twenty-four elements high and contained seventy-two elements; therefore, the scan surface required at least 216 total scan points. However, for greater accuracy, more scan points were specified. A 1152 scan point distribution with ninety-six scan point rows and twelve scan point columns over the front column surface was chosen. This distribution yielded an average nineteen scan points per element or approximately nineteen scan points per square inch (6 cm^2). Only one column face was selected as the scan surface; the two braces and the other column were ignored. Surfaces associated with these structure features were ignored mainly because scan times were

[16] The width and corner radius of curvature for each RHS member was 3.0 in. (76 mm) and 0.25 in. (6.3 mm), respectively; therefore, the actual flat surface width across each column face was 2.5 in. (6.3 mm).

long and non-stationary data was possible. The data acquisition system averaged about three seconds at each scan point. At this rate, each column front surface scan averaged almost an hour; hence, the three total scans averaged nearly three hours. The same scan point distribution across all other test structure feature surfaces, say front surfaces only, would have added nearly another 100 minutes to each scan. Clearly this was unacceptable. However, though other test structure features were ignored, ESDM evaluation was not affected. The column front surface provided the necessary scan surface for reconstruction of a surface velocity field which possessed large in-plane and small out-of-plane velocity components.

Fourth, an ESDM evaluation standard was considered. Accurate ESDM evaluation dictated that ESDM results be compared with experimental data obtained from an independent measurement standard separate from the LDV. Accelerometers were ultimately selected for this purpose. Specifically, a tri-axial accelerometer configuration with accelerometers mounted in three orthogonal directions ultimately enabled independent velocity measurement along three orthogonal directions at discrete test structure locations

The tri-axial accelerometer configuration consisted of three PCB model 303A02 accelerometers threaded into a small steel mounting block. Each accelerometer casing indicated the minimum transverse sensitivity axis[17]. Thus, the accelerometer chosen to measure in-plane acceleration in the *x*-direction was oriented so that its minimum transverse sensitivity axis was aligned with the sensing axis of the accelerometer chosen

[17] The minimum transverse sensitivity axis for each accelerometer was specified by PCB Piezotronics, Inc.

to measure out-of-plane acceleration in the *z*-direction. Likewise, the accelerometer chosen to measure out-of-plane acceleration in the *z*-direction was oriented so that its minimum transverse sensitivity axis was aligned with the sensing axis of the accelerometer chosen to measure in-plane acceleration in the *x*-direction. The remaining accelerometer which measured vertical acceleration in the *y*-direction was oriented such that its minimum transverse sensitivity axis was aligned with the sensing axis of the accelerometer which measured *x*-direction acceleration. Unfortunately, this meant that its maximum transverse sensitivity axis was aligned with the sensing axis of the accelerometer which measured *z*-direction acceleration; however, although this was unavoidable, it did not pose a problem since acceleration in the *y*-direction was negligible and relatively unimportant as far as ESDM evaluation was concerned.

The velocity components obtained from the accelerometer data permitted ESDM evaluation. These components were compared with ESDM results obtained at the points where the accelerometers were affixed to the column front surface. A match between component sets, especially components in the *x*- and *z*-directions, indicated that ESDM accurately reconstructs surface velocity fields with large in-plane and small out-of-plane components.

The mounting block is a 0.25 in. (6.3 mm) cube. Therefore, the accelerometers were actually located 0.25 in. (6.3 mm) from the test structure front surface and exact surface accelerations were not measured. To determine whether this posed a problem, the original finite element model of the final test structure design was modified to include the tri-axial accelerometers and mounting block. The model was excited exactly as specified previously so that five percent out-of-plane motion in the z-direction relative to in-plane motion in the z-direction was generated at 144 Hz. Then velocity components were obtained at 1) the point where the accelerometers were affixed to the column front surface and 2) the points where the accelerometers were threaded into the mounting block. Comparison between the results indicated no significant differences between similar components at the column front surface and interfaces between the accelerometers and mounting block. Thus, it was reasonably assumed that the accelerometers accurately measured velocity components at the actual front surface.

Last, scanner control and data acquisition systems were considered. Figure 51 schematically describes both systems. Scanner control instructions were automatically

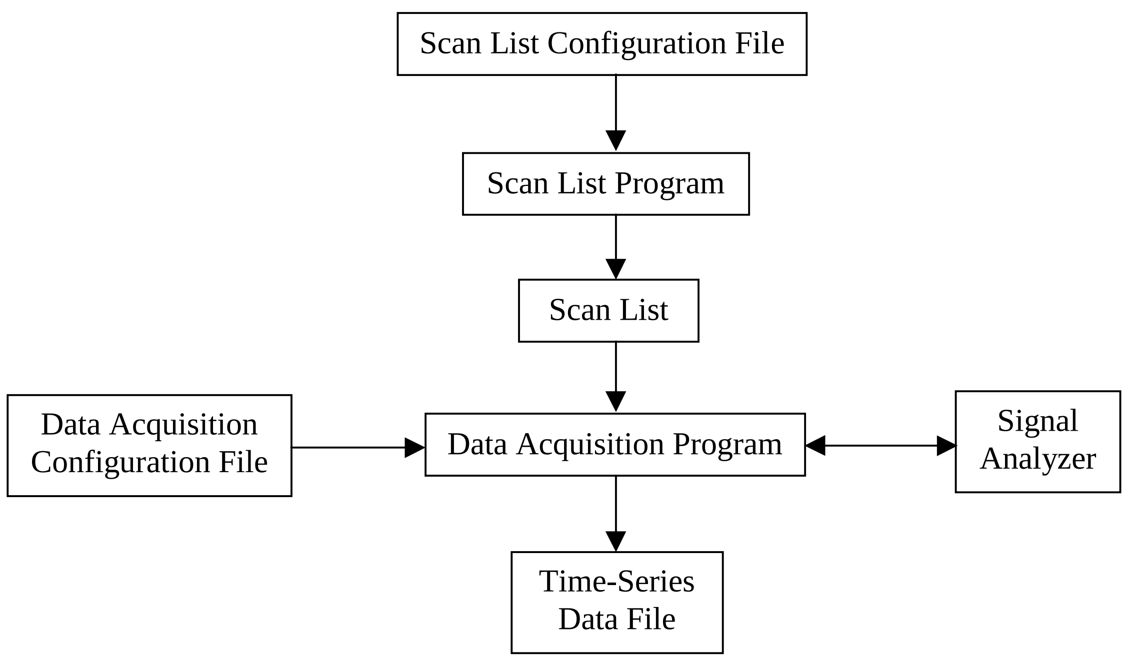

Figure 51. Scanner control and data acquisition systems

created by an ESDM computer program developed by West [58] and installed on the Silicon Graphics Crimson® workstation previously mentioned. From information contained within a scan list input file which specified the scan surface boundary and the scan point distribution, the program calculated the DAC coordinates of each scan point. This information was then written to a scan list file for later use by the ESDM program that controlled data acquisition.

The data acquisition system was centered around a Hewlett-Packard model 35665A digital signal analyzer. The signal analyzer acquired all experimental data. It was automatically and remotely controlled by another ESDM computer program created by West [59] and installed on the same workstation. This program 1) read a configuration file and subsequently set the time period over which data was acquired at each scan point, the data sampling rate, the maximum dynamic range for each data channel and the trigger condition, 2) collected the data acquired at each scan point and 3) wrote it to a time-series data file in a specific format that permitted eventual processing by ESDM. The program also read the scan list file and generated the DAC steps that directed the LDV scanners.

Experimental Approach

The experimental approach was extremely straightforward since the scanner control and data acquisition systems were fully automated. First, accelerometer measurements in the *x*, *y* and *z*-directions were specified at the column front surface location indicated by Fig. 52. Second, four front surface scans were mandated from four well separated, non-coplanar LDV positions. At least three scans were needed for ESDM

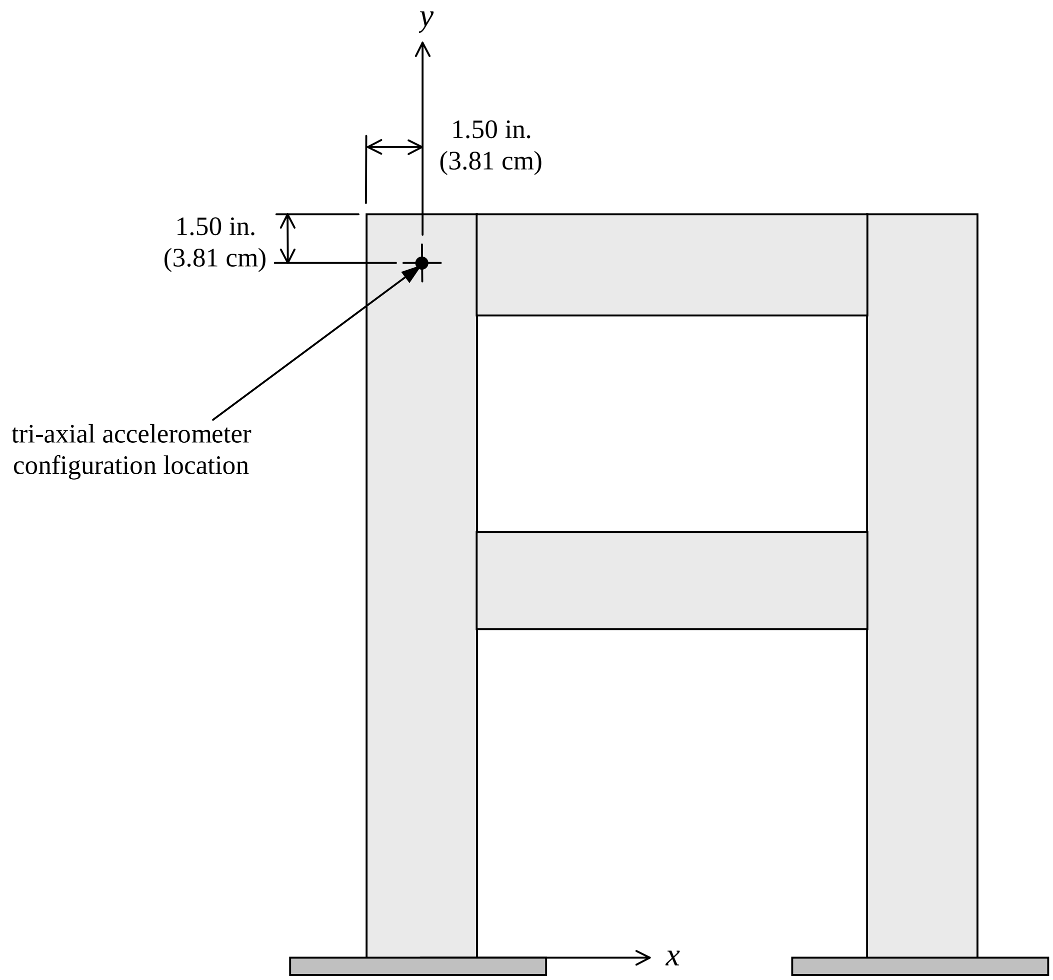

Figure 52. Tri-axial accelerometer configuration placement

velocity field reconstruction; however, a fourth scan yielded greater accuracy since velocity field reconstruction via ESDM relies upon a least squares formulation. Last, accelerometer measurements were specified at the six front surface locations indicated by Fig. 53.

Accelerometer measurements were specified before and after the column front surface scans. Concern about non-stationary data influenced this decision. Accelerometer measurements taken earlier indicated that ambient temperature variations

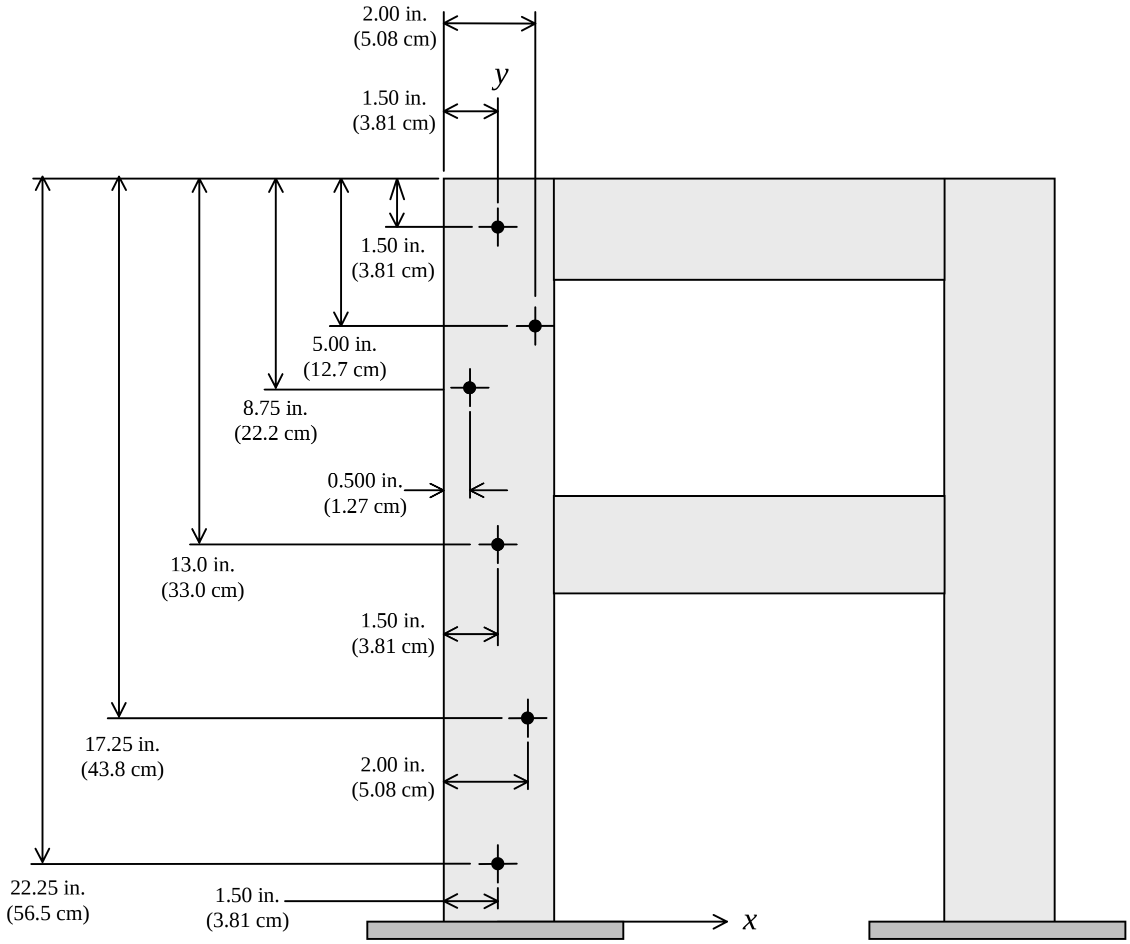

Figure 53. Tri-axial accelerometer configuration placement at multiple front surface locations

slightly affected test structure motion. Thus, since the LDV scans consumed so much time, slightly non-stationary LDV velocity and accelerometer data was expected. Unfortunately, such non-stationary effects, most likely attributable to the test structure and its tempeature-sensitve boundary conditions, were unavoidable. However, non-stationary effects present in the accelerometer data were minimized. Taking accelerometer measurements at two different times ultimately permitted averaging and helped minimize non-stationary effects.

Accelerometer measurements at multiple column front surface locations were specified only once after the LDV scans were completed. Three concerns influenced this discussion. First, as before, non-stationary data was a concern. The total time required for accelerometer data acquisition at one position averaged about nine minutes. Consequently, data collection at six locations required almost one hour. Accelerometer measurements at the same six locations an additional time would have required nearly another hour. Second, accelerometer repositioning was a concern. Since exact repositioning was not possible, moving the accelerometers would have introduced uncertainty into the acceleration data. Last, possible dynamic response changes were a concern. Moving the accelerometers over the column front surface may have affected structural dynamic response. Hence, unwanted velocity data variations were possible. Consequently, accelerometer measurements at multiple front surface locations were conducted only after the LDV scans were completed.

Experimental Procedure

Once the experimental approach was formulated, the experimental procedure was implemented. It followed the general procedure outlined by the experimental approach. This section presents the experimental procedure.

The experimental procedure began with equipment preparation. First, the test structure excitation components previously described were assembled at the location indicated by Fig. 49. Figure 54 shows the final excitation arrangement: 1) a Brüel & Kjær[18] model 4210 shaker was suspended from the ceiling by a bungee cord, 2) the

[18] Brüel & Kjær AB, Skodsborgvej 307, DK-2850 Nærum Denmark

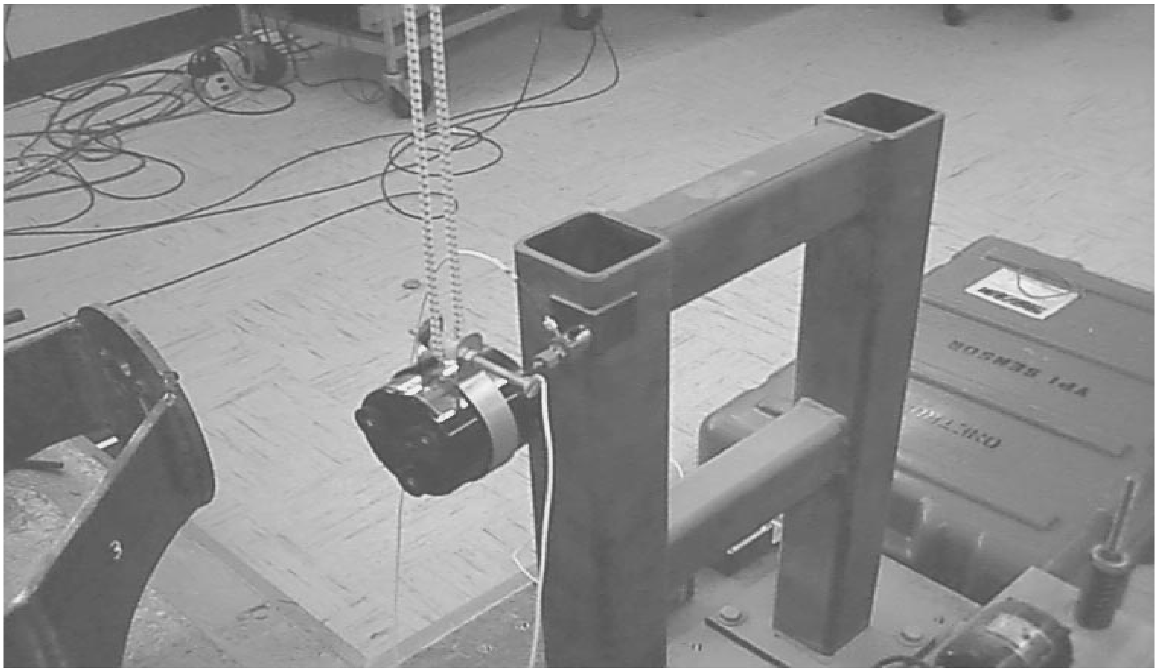

Figure 54. Test structure excitation arrangement

stinger was threaded into the shaker at one end and the other end was threaded into a PCB model 288D01 impedance head and 3) the impedance head was threaded into the boss already affixed to the structure at the location indicated by Fig. 49. The force transducer was powered by a PCB model 480A power unit.

Second, the column front surface was coated with a retro-reflective material manufactured by 3M[19]. The material consists of extremely small glass beads which helped reflect laser light back to the LDV. The beads adhered to thin oil film applied to the front surface. The front surface was sprayed with WD-40®[20] brand oil and the glass beads were blown onto it.

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[19] 3M Corporation, 3M Center, St. Paul, MN 55144
[20] WD-40 Company, San Diego, CA 92110

Third, the tri-axial accelerometer configuration was mounted with accelerometer wax at the column front surface location indicated by Fig. 52 and pictured in Fig. 55. At this position, the three accelerometers measured horizontal in-plane acceleration in the *x*-direction, out-of-plane acceleration in the *z*-direction and vertical in-plane acceleration in the *y*-direction. The accelerometers were each powered by a PCB model 480C06 power unit.

Fourth, the LDV was prepared for the first front surface scan. The LDV, already

Figure 55. Tri-axial accelerometer configuration location

secured to a tripod, was positioned at the location indicated by Fig. 56 at the minimum tripod elevation. Two shielded cables were connected to the LDV; these cables carried the velocity signal and Doppler signal[21].

Fifth, the signal analyzer was prepared. A cable from the force transducer power unit was connected to one signal analyzer data channel and a cable from the

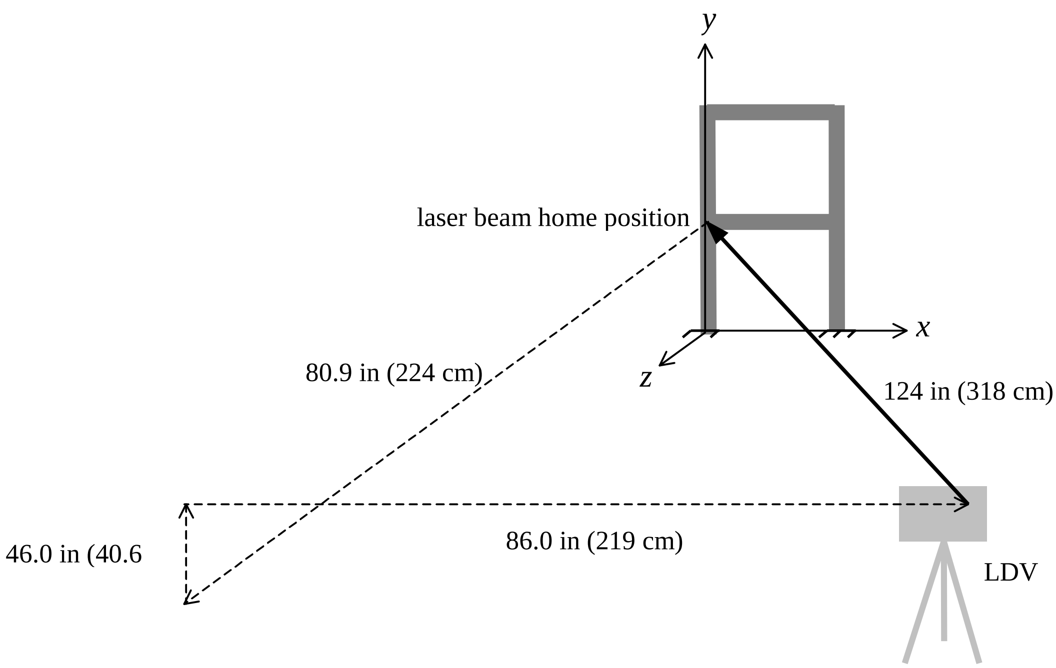

Figure 56. LDV position for first front surface scan

accelerometer power unit was connected to the other data channel. The signal analyzer generated the test structure excitation signal. Therefore, a cable was connected between the signal analyzer source channel and a Harmon/Kardon[22] model hk770 power amplifier that powered the shaker. Another cable between the signal analyzer and a National

[21] The velocity signal is derived from the Doppler signal [60].
[22] Harmon/Kardon, Inc., 80 Crossways Park West, Woodbury, NY 11797

Instruments[23] model GPIB-SCSI-A general purpose interface bus (GPIB) controller allowed communication between the signal analyzer and the workstation.

Sixth, a Tektronix[24] model 2214 oscilloscope was prepared. Cables from the signal analyzer source channel and data channels were connected to three separate oscilloscope channels. The oscilloscope permitted visualization of the test structure source excitation signal, force transducer signal and accelerometer signals. Seventh, the acoustic digitizer originally used for LDV scanner calibration was prepared. The digitizer aided LDV registration. The digitizer microphone array was placed near the column front surface, the digitizer system was turned on and then calibrated.

Last, the LDV, signal analyzer, power amplifier, workstation and oscilloscope were all plugged into one wall socket via a power strip with multiple sockets. This eliminated any electrical ground problems such as ground loop currents. The equipment was then turned on three hours before any accelerometer data was collected so that steady-state thermal operating conditions were achieved.

After the equipment had achieved steady-state operating conditions, the shaker excitation signal was generated via the signal analyzer and the shaker excited the test structure. A 250 mV zero-to-peak sinusoidal excitation signal at 144 Hz was generated.

Subsequently, accelerometer data was collected. First, in-plane accelerometer data in the *x*-direction was collected. A cable from the accelerometer which measured in-plane acceleration was connected to the power unit, the power unit was turned on and the power unit gain was set to ten. Frequency-domain data was then collected and averaged

[23] National Instruments Corporation, 6504 Bridge Point Parkway, Austin, TX 78730

twenty-five times by the signal analyzer across a 400 Hz frequency span[25] and 800 spectral lines. Specifically, acceleration linear spectrum, mobility and coherence data were collected. Only raw data were collected; sensitivity factors were applied later during processing.

Second, vertical accelerometer data in the *y*-direction was collected. The power unit was turned off, the cable from the accelerometer which measured in-plane acceleration was disconnected from the power unit, the cable from the accelerometer which measured vertical acceleration was connected to the power unit, the power unit was turned on and the gain was set to ten. Again, acceleration linear spectrum, mobility and coherence data were collected and saved on disk by the signal analyzer.

Last, out-of-plane accelerometer data in the *z*-direction was collected. The process previously described was again followed and acceleration linear spectrum, mobility and coherence data were collected and saved on disk by the signal analyzer.

After accelerometer data was collected, a Cartesian coordinate system was created on the column front surface by the digitizer. This coordinate system, henceforth referred to as the front surface coordinate system, was aligned with the test structure coordinate system defined by Fig. 22; later it helped define registration point coordinates ultimately needed for LDV registration.

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[24] Tektronix, Inc., 26600 Southwest Parkway, P.O. Box 1000, Wilsonville, OR 97070

[25] 2.5×10^{-2} s time period

Subsequently, the first front surface scan was conducted. First, the LDV was oriented such that the laser beam at its home position[26] illuminated a point near the geometric center of the column front surface.

Second, the cable from the accelerometer power unit was disconnected from both the signal analyzer and oscilloscope and the cable that transmitted the LDV velocity signal was inserted into the empty signal analyzer and oscilloscope channels. Also, the cable that transmitted the LDV Doppler signal was connected to the oscilloscope. Now, the oscilloscope permitted visualization of the excitation signal, the force signal and the LDV velocity and Doppler signals during each front surface scan.

Third, the laser beam illuminated eight arbitrary but well spaced registration points on and off the test structure. Laser beam movement was controlled by a graphical user interface (GUI) program originally created by Coe [61] and installed on the workstation. The GUI program generated the necessary DAC steps which controlled the LDV scanners. At each registration point, 1) its coordinates in the front surface coordinate system were recorded by the digitizer and 2) its DAC coordinates were recorded. Another program included with the ESDM software suite later processed this information and calculated the required LDV transformation matrix.

Fourth, the scan list input file which specified the scan surface boundary and scan point distribution was created. Points at each front surface corner were illuminated by the laser beam and the corresponding DAC coordinates at each corner were recorded.

[26] The home position is the position at which the applied voltage to each LDV scanner is zero.

This information and the scan point distribution over the front surface were put into the scan list input file. The program that calculated the scan list was then executed. This program read this file and generated the scan list.

Fifth, the signal analyzer configuration file was created. This file specified several data acquisition parameters for the signal analyzer including the time period over which data was acquired at each scan point, the data sampling rate, the maximum dynamic range for each data channel and the trigger condition. Ultimately, the data acquisition program read the file and configured the signal analyzer before data was acquired. Table 8 lists the data acquisition parameters.

Table 8. Signal analyzer data acquisition parameters

Time Window (ms)	**Data Sampling Rate** $\left(\frac{\text{samples}}{\text{s}}\right)$	**Full Scale Range**		**Trigger Condition**
		Force Channel (mV)	**Velocity Channel (mV)**	
27.8	9216	300	1000	immediate[27]

Last, the first front surface scan was actually conducted by executing the data acquisition program. The program 1) read the signal analyzer configuration file and configured the signal analyzer, 2) read the scan list file and sequentially directed the laser beam to each scan point and 3) collected time-series data at each scan point and wrote it to the time-series data file. After the first front surface scan was completed, the three other front surface scans were conducted. The procedure followed for the first front surface scan was again followed for these scans. The only difference is the LDV was

[27] Data acquisition occured immediately after a trigger command from the data acquisition program was received.

moved to different locations. Figures 57, 58 and 59 show the LDV locations relative to the test structure for the second, third and fourth scans, respectively.

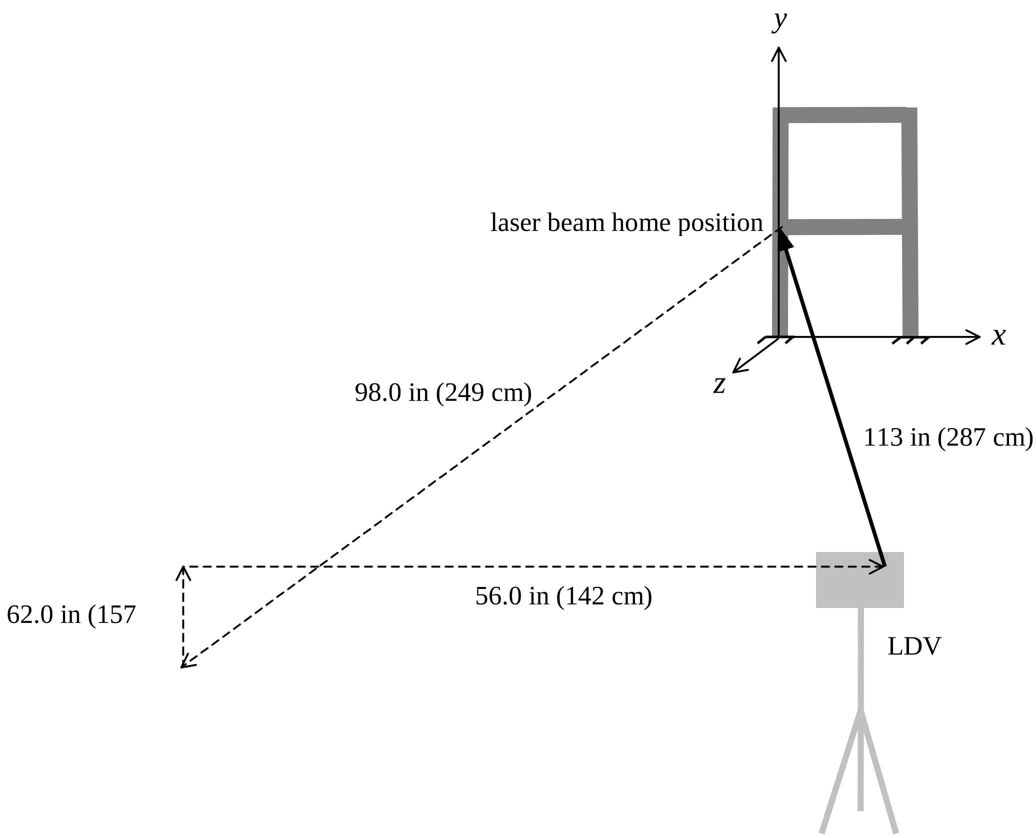

Figure 57. LDV position for second front surface scan

Finally, after the LDV scans were completed, accelerometer data was collected again. The cables from the LDV were disconnected from the signal analyzer and oscilloscope and the cable from the accelerometer power unit was reconnected. The same accelerometer data collection procedure was used; however, this time the accelerometer configuration was placed at five additional front surface locations.

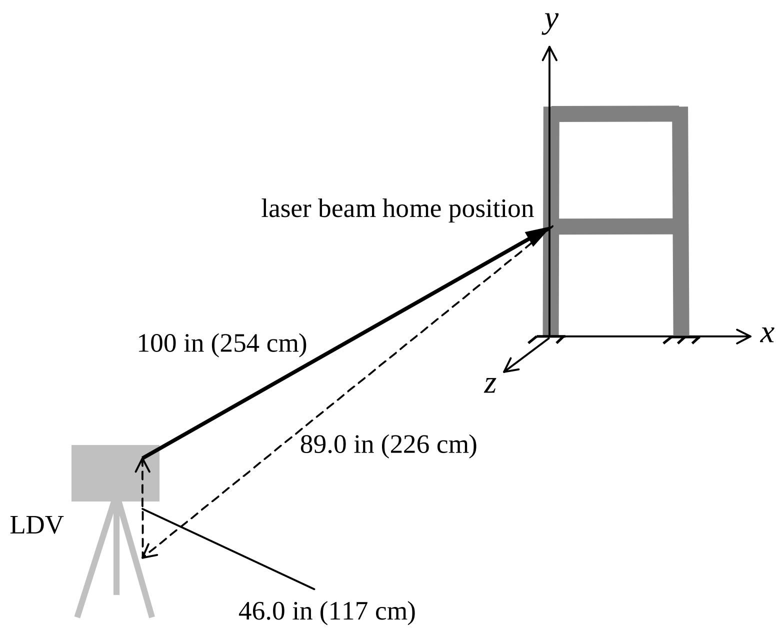

Figure 58. LDV position for third front surface scan

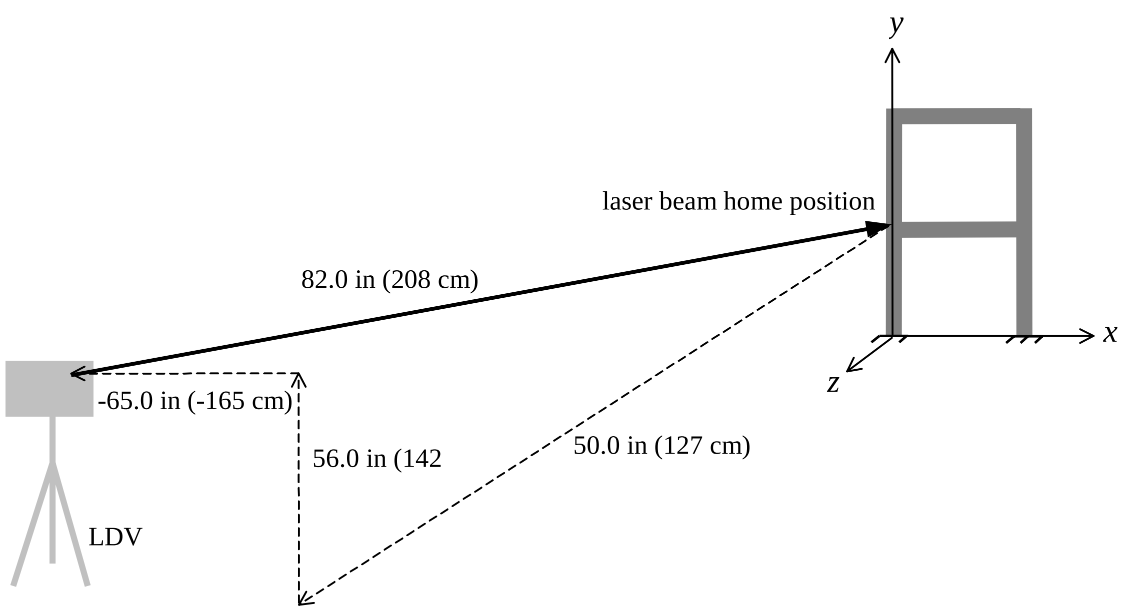

Figure 59. LDV position for fourth front surface scan

The entire experimental procedure required approximately eight hours: four hours for equipment preparation and an additional four hours for data acquisition. It yielded velocity and registration data which ultimately allowed velocity field reconstruction by ESDM. It also provided accelerometer data against which ESDM results were compared and evaluated.