Validating and Assessing Integrity of Troubled Bridges in Connecticut: Monitoring Cable Tensions For the Arrigoni Bridge, Middletown, CT

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16. Abstract

This report provides information on a study of the Arrigoni Bridge in Middletown, Connecticut, where vibration measurements are used to determine the tension among various suspender cables in the structure. Actual vibration data on 134 cables under ambient, traffic-induced excitation is used to determine the corresponding natural frequencies and, along with cable parameters, calculate the tension in each cable.

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INTRODUCTION

The Arrigoni Bridge, located in Middletown, CT, over the Connecticut River, is a steel through-arch bridge with vertical helical steel rope suspenders supporting the deck and superstructure connecting to the upper steel truss. A picture of the bridge is shown in Figure 1. This research will examine the tension in the suspender cables on the main Eastern span (Span #11) of the bridge using cable vibration measurements. The vibration of the cables is simplified using taut-string theory. Experimental data consisting of the transverse acceleration of the cable motion is collected under ambient loading conditions. This report provides background information on the theory behind estimating the tension of a cable using vibration data. This is followed by a description of the sensors and data acquisition system used to collect the acceleration response of the cables to normal traffic loading. Next, a description of the bridge suspender cables is provided. Finally, the cable tensions for each of the 134 cables are provided and conclusions presented.

Figure 1. Arrigoni Bridge, Middletown, Connecticut

THEORY OF ESTIMATING CABLE TENSION FROM VIBRATION DATA

Steel cables, such as those found on the Arrigoni Bridge, can effectively be modeled as a taut-string. Taut-string theory in this study is used to determine the cable tension from the vibrations of the cable. This section provides a brief background on the theory of cable vibration for a taut-string (Irvine, 1981).

The suspender cable is modeled as a vertical cable of length L pinned at each end, as shown in Figure 2. The cross-sectional area, A, of the cable is assumed to have an equivalent area of the 1x73 strand cables. In the taut-string model, bending stiffness is neglected. The significance of this assumption is examined in Appendix A of this report. In Appendix A, it is demonstrated that including bending stiffness increases the complexity of the analysis significantly (the tension is no longer determined from an algebraic equation, but must be solved for iteratively) yet only results in calculated tensions for the Arrigoni Bridge cables with a difference of less than 2%. As such, bending stiffness is ignored and the taut-string model is used. The mass per unit length of the cable, m, is determined from the mass density of steel, ρ, and the cross sectional area as $m = \rho A$.

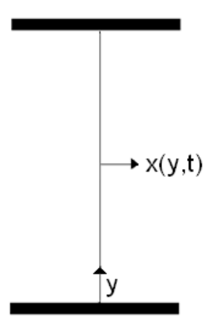


Figure 2. Suspender Cable Modeled as Taut-String

When the cable is under excitation, the forces propagate through the cable and the wave equation is applied for equilibrium:

$$mx - Tx'' = 0 \tag{1}$$

where *m* is the mass per unit length of the cable, *T* is the tension in the cable, $x = \frac{\partial^2 x}{\partial t^2}$ is the cable acceleration, and $x'' = \frac{\partial^2 x}{\partial y^2}$ is the second derivative of cable position with respect to position along the cable.

As a force wave travels along the cable, its shape does not change. The wave translates along the length of the cable maintaining the same shape. The static behavior of this shape is given by $x(y,0) = f(y)$, where $f(y)$ is a generalized function. Once it starts traveling along the length of the cable in time, a factor is added to the equation in order to adjust for the movement of the traveling wave:

$$x\;\; y,t\;\; = f(y - vt) \tag{2}$$

Where $f(.)$ is the generalized traveling wave representation of $x(y,t)$, y is the vertical position in consideration, $v = \frac{\partial x}{\partial t}$ is the speed of the wave and t is the time at which $x(y,t)$ is being analyzed. For easier analysis, y-vt is substituted for a single variable, $u = y\text{-}vt$. In order to implement this substitution into the wave equation, the second derivatives with respect to both time and position are presented below:

$$\frac{\partial^2 f}{\partial t^2} = v^2 \frac{\partial^2 f}{\partial u^2} \tag{3}$$

$$\frac{\partial^2 f}{\partial y^2} = \frac{\partial^2 f}{\partial u^2} \tag{4}$$

Substituting Equation 3 and Equation 4 into Equation 1 results in a new equation:

$$\frac{\partial^2 f}{\partial u^2}\;\; mv^2 - T\;\; = 0 \tag{5}$$

There are two solutions to Equation 5, the first is the trivial solution $\frac{\partial^2 f}{\partial u^2} = 0$. The physical meaning of this solution is that the cable is not moving. The second solution is:

$$mv^2 - T = 0 \;\; \rightarrow \;\; v^2 = \frac{T}{m} \tag{6}$$

The speed of the wave traveling along the cable is only dependent on the tension force in the cable, *T*, and the mass per unit length of the cable material, *m*.

The cables undergo harmonic oscillations that allow the velocity component in Equation 6 to be written in another form using the natural frequency of the cable, ω_1. The relationship between velocity and frequency of a simple harmonic wave is:

$$v = \lambda f_1 = \lambda \frac{\omega_1}{2\pi} \tag{7}$$

Where λ is the wavelength, f_1 is the frequency of oscillation in Hz and ω_1 is the frequency in rad/s. For the first mode vibration, the cable undergoes a half sine wave deformed shape such that $\lambda = 2L$. Substituting this relationship into Equation 6 yields:

$$\frac{\omega_1 L}{\pi}^{\;\;2} = \frac{T_1}{m} \tag{8}$$

Evaluating the exponent and rewriting to solve for the tension force in the cable, T_1, yields the equation:

$$T_1 = \frac{m{\omega_1}^2 L^2}{\pi^2} \tag{9}$$

Equation 9 represents the fundamental frequency mode solution for the tension force. Higher order modes can also be evaluated with the same approach as above in order to generate multiple equivalent equations for the tension force. For the nth mode, the wavelength is such that $\lambda = \frac{nL}{2}$. Inserting this relationship into Equation 7 and writing it in the same form as Equation 9 yields:

$$T_n = \frac{m\omega_n^2 L^2}{n^2\pi^2} \tag{10}$$

where T_n is the tension force of mode *n* and ω_n is the *n*th natural frequency. Since the cable is in equilibrium under a single tension force, $T_1 = T_n$, Equation 9 and Equation 10 are set equal.

After cancelling like terms and rearranging the variables, the final relationship between ω_1 and ω_n is:

$$\omega_n = n\omega_1 \qquad (11)$$

This relationship will be used later in the report to confirm the experimental data matches the taut-string prediction and that the use of this model is valid.

SENSORS AND DATA ACQUISITION EQUIPTMENT

A Bridge Diagnostics Incorporated (BDI) Structural Testing System (STS) Wireless system is used to collect the cable vibration measurements. The system is comprised of one STS-WiFi Base Station, three STS-WiFi Nodes, twelve 50g accelerometers, and one Laptop PC. The accelerometers are attached directly to the suspender cables with Velcro straps 5 feet above the bridge deck and have a wired connection to the STS-WiFi Nodes. The accelerometers are oriented in the North-South direction (transverse to the roadway) on the cables. Data is collected at a sampling rate of 100 Hz under normal ambient traffic and wind conditions. The Nodes transmit sensor readings wirelessly to the STS-WiFi Base Station. The STS-WiFi Base Station aggregates the data and then transmits it wirelessly to the PC where it can be viewed and stored. Supplemental information on the STS-WiFi base station and nodes, as well as the calibration information for the 50g accelerometers can be found in Appendix B. A picture of the system as deployed on the Arrigoni Bridge can be found below in Figure 3.

Figure 3. BDI STS-WiFi System Deployed on Arrigoni Bridge

BRIDGE SUSPENDER CABLES

The Arrigoni Bridge suspender cables were examined in 2007 (Martyna, 2007). At that time, the cables were inspected by magnetic flux non-destructive testing to determine the overall condition of the suspender cables. It was observed in 2007 that the cables did not appear to exhibit signs of serious deterioration. Over 93% of the cables tested showed less than 1% cross-section loss. For the remaining 7% of the cables, signs of broken wires or loose wires and moderate corrosion were observed. Due to this investigation, the suspender cables in this report will be treated as having the full cross-sectional area of the cables at installation. The cable labeling from the 2007 report is used in this report and is shown in Figure 4. The cable numbers line up with vertical sections of the steel truss and consist of numbers 2 through 18. Within each cable set, the individual cables are labeled numbers 1 through 4, starting in the SW corner and continuing clockwise. Cables on the North side of the span have an 'N' added on the end of the label. For example, Cable Set L3 on the North side is labeled L3N. Cables on the South side of the span do not have any added characters.

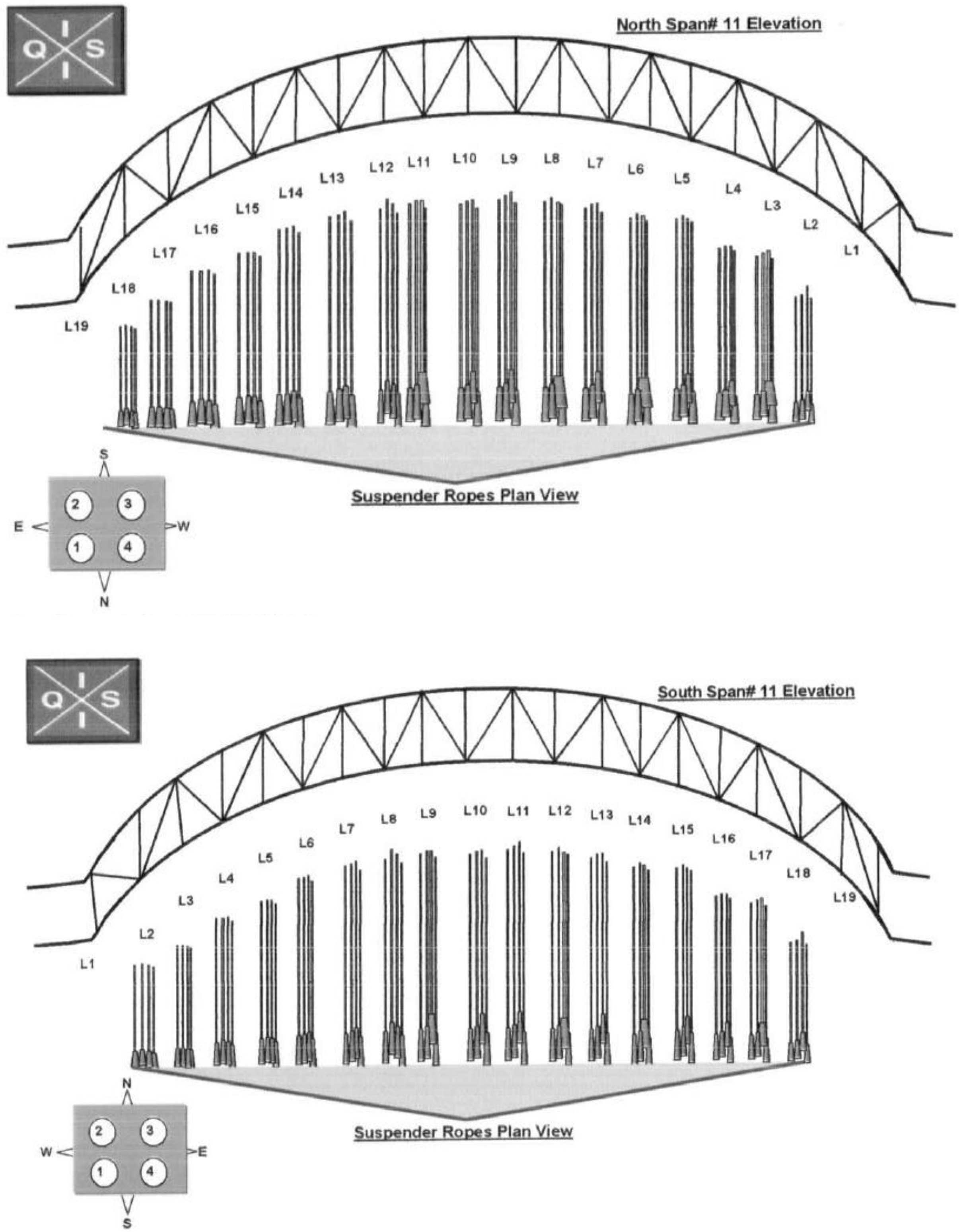


Figure 4. Cable Identification Diagram (Martyna, 2007)

The cable lengths were determined from the bridge plans and a site visit. The lengths of the four cables in each cable set are assumed to be equal. The cable lengths are rounded to the nearest foot, which results in potential error in the tension measurement from 1.3% to 9% for the longest to shortest cables, respectively.

Table 1. Cable Lengths

Cable Set	L2/L18	L3/L17	L4/L16	L5/L15	L6/L14	L7/L13	L8/L12	L9/L11	L10
Length (ft)	11	26	39	50	59	66	71	74	75

The cross-sectional area of the cables was determined from ASTM A586 to be 1.59 in^2 (0.01104 ft^2) with a diameter of 1.625 inches. The mass per unit length of the cables was determined using the cable material density multiplied by the cross-sectional area. The cables were assumed to have been made of standard structural steel, which has a density of 490 lb/ft^3. This resulted in a weight per unit length of 5.41 lb/ft and a mass per unit length of 0.168 $lb\text{-}s^2/ft^2$.

POWER SPECTRAL DENSITY FUNCTION

The power spectral density function is used to determine the natural frequencies of the suspender cables. The power spectral density function is a measure of the system energy at each frequency. Accelerations are recorded for a time period and can be transformed into the frequency domain by the Fourier Transform. The Fourier Transform uses the time history acceleration, $x_k(t)$, and transforms it into a frequency domain, $X_k(f,T)$, as follows (Bendat and Piersol, 2010):

$$X_k(f,T) = \int_0^T x_k(t)\, e^{-j2\pi t f} dt \qquad (12)$$

where f is a given frequency in Hz and T is the finite time interval over which the transform is performed and k is the number of segments that the data series is segmented into. Once the acceleration data has been transformed, the power spectral density function can be used. This function has the following form:

$$G_{xx}(f) = 2\lim_{T\to\infty} E\left[\left|X_k(f,T)\right|^2\right] \tag{13}$$

Where $G_{xx}(f)$ is the power spectral density function of the acceleration signal, and E[.] is the function for the expected value of the term $|X_k(f,T)|^2$, also known as the weighted average value for the function.

From the PSD function, the natural frequencies of the cables can be determined. At the cable natural frequencies, resonance occurs and this is present in the PSD function plot at locations where sharp peaks exist. These peaks were selected as the natural frequencies for each cable for use in the tension force calculation.

USING ACCELERATION DATA TO DETERMINE RMS OF DISPLACEMENT

The amplitude of cable vibration was one of the initial concerns that prompted this study. It was determined to use acceleration data to examine the potential for high vibration amplitude cables. One approach to determine displacements from acceleration data involves computing numerical integrals of the signal to obtain approximate velocity and repeating the process to achieve approximate displacements. This approach has some difficulties associated with integrating a discrete noisy signal. In order to overcome these difficulties, the root-mean squared (RMS) displacements are determined in the frequency domain using measured cable acceleration. This *omega arithmetic* uses the transformed signal in the frequency domain to take advantage of simple algebraic relationships between acceleration, velocity and displacement.

The goal of this approach is to evaluate the root-mean square displacement, RMS_d, value for every cable to try to determine which cables have higher amplitude vibration and to investigate why certain cables seem to have higher amplitude vibration. For a given acceleration signal, $x(t)$, the signal can be transformed into the frequency domain by the Fourier Transform. The transformed signal, $X(f)$, contains the exact same information as the original signal, but now is examined in the frequency domain. The algebraic relationship between acceleration and displacement in the frequency domain is given by:

$$X(f) = \frac{-1}{\omega^2} X(f) \tag{14}$$

where $X(f)$ is the displacement in frequency domain and ω is the frequency in rad/s. The parameter of interest is the RMS of displacement. Writing the relationship in Equation 14 in terms of the power spectral density (PSD) function, through Equation 13, reveals that:

$$G_{xx}(f) = \frac{1}{\omega^4} G_{xx}(f) \tag{15}$$

where $G_{xx}(f)$ is the auto-power spectral density (PSD) function for displacement and $G_{xx}(f)$ is the PSD function for acceleration and ω is the frequency (in rad/sec). The PSD function is defined fully in the previous section of this report. Taking the integral between any two frequencies, f_1 and f_2, of $G_{xx}(f)$ is related to the RMS value as:

$$RMS_d(f_1, f_2) = \sqrt{\int_{f_1}^{f_2} \frac{1}{(2\pi f)^4} G_{xx}(f)\, df} \tag{16}$$

where RMS_d is the RMS of displacement. Equation 16 can now be used to determine the displacement RMS for a given acceleration signal $x(t)$.

USING MULTIPLE MODES TO DETERMINE NATURAL FREQUENCY

From a previous section discussing the background for taut-string theory, the increasing natural frequencies of a taut-string vary linearly by the relationship $\omega_n = n\omega_1$, where n is the nth mode of vibration and ω_1 is the fundamental frequency of the cable. The first four natural frequencies, ω_1 to ω_4, are used in this study to determine the linearity of the natural frequencies. Each of these four frequencies is used in a linear regression to determine the best fit line by residual least squares error approximation. The slope of this fit line, ω_1, in the following calculations and the norm of the residuals, *Norm of R*, are displayed to give an indication of the goodness of fit for the linear approximation.

RESULTS

Data was collected on March 8th, 2011. The results of the cable force estimation are given in Table 2. Table 2 is simplified to show only the cable tension force for each cable. More information on the acceleration time history, power spectral diagram plot and linear regression fit line are provided in Appendix C for a much more in-depth look at each of the cable behaviors. Appendix C also allows direct comparison between cables within a set and between cables sets, documenting the measured behavior of each cable. In addition, Appendix C contains tables that give numerical values for the four natural frequencies, ω_1 to ω_4, as well as the fitted natural frequency, ω_1, and the goodness of fit parameter, *Norm of R*.

Table 2. Cable Tension Forces

South Force (k)				
Cable	1	2	3	4
L2				
L3	48.87	50.36	71.61	99.59
L4	49.24	45.49	54.07	69.12
L5	51.21	42.12	39.21	41.39
L6	42.13	48.47	38.70	41.74
L7	50.55	43.11	49.13	49.49
L8	49.38	36.98	37.75	56.72
L9	46.60	39.22	37.82	35.77
L10	49.73			46.30
L11	39.22	37.94	37.13	46.60
L12	50.65	43.85	42.78	41.26
L13	48.78	60.79	42.89	45.67
L14	37.41	43.40	48.58	48.47
L15	47.38	42.37	42.70	38.42
L16	55.03	67.72	54.22	72.11
L17	61.34	64.53	55.20	46.46
L18				

North Force (k)				
Cable	1	2	3	4
L2N				
L3N	45.07	61.65	63.48	64.53
L4N	73.12	39.68	65.30	65.54
L5N	51.30	54.91	31.95	38.34
L6N	53.72	57.74	53.28	46.61
L7N	44.33	48.43	52.84	46.13
L8N	51.04	47.00	46.88	41.49
L9N	40.53	39.81	41.37	52.95
L10N	42.99	45.01	46.82	45.01
L11N	42.22	37.59	37.25	50.79
L12N	47.25	44.44	43.61	47.75
L13N	54.31	50.43	52.96	47.73
L14N	43.50	51.87	50.58	44.89
L15N	54.44	51.21	39.05	41.14
L16N	74.74	46.30	67.72	83.81
L17N	53.64	43.93	66.24	59.44
L18N				

As seen in Table 2, cables L10-2 and L10-3 do not have tension force values. This is a result of a ladder that is attached to the cables for access to the upper steel truss. Because of the added mass on the cables, the mathematical model of the taut-string cannot be applied. All of the cables in sets L2, L2N, L18 and L18N do not have any force results because the ambient excitation for these cables is not sufficient to accurately determine any of the natural frequencies for these cables.

Of additional note, there is one cable that has a tension force value double the average force. Cable L3-4 has a force value of 99.59 kips. This cable and L3-3, L16-4, L4N-1, L16N-1 and L16N-4 have tension forces more than 25 kips above the average and may experience more issues with axial fatigue and should be inspected more thoroughly.

The variation in the four cables at each location is also noted to vary significantly from set to set with no observed pattern. The average difference between the maximum and minimum tensions of cables in a set is 15.3 kips. Some cable sets have larger variation in the tensions, namely L3, L4N, and L16N with variations of 50.72, 33.44, and 37.51 kips, respectively.

In order to visualize how the cable forces vary, all of the forces from Table 2 are presented in Figure 6 below.

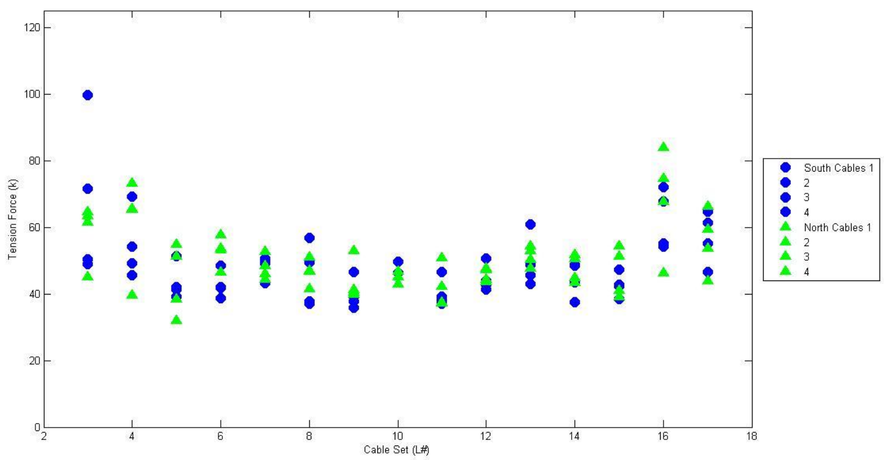


Figure 5. Cable Tension Forces

It is evident in Figure 5 that cable sets 3, 4, 16 and 17 have higher estimated tension forces for both the south and north sides of the bridge. Cable sets 5 through 15 show a uniform force value that would be expected for this bridge type. Cable tension forces for the original system have been determined using taut-string theory and experimental acceleration data.

DISPLACEMENT RMS RESULTS

The displacement RMS values for each of the cables are computed using the acceleration time history and Equation 16 previously described. For all of the cables, the maximum RMS value is below 0.0025 inches. This value is very small, and thus, cable vibration amplitude does not seem to be an issue for these cables. During visual inspection of the cables, there seems to be no apparent relationship between length of cable and the vibration amplitude. Table 3 presents the displacement RMS values for each of the cables of Span 11 of the Arrigoni Bridge.

Table 3. Displacement RMS Values

South		
		RMSd (in)
L3	1	0.001474
	2	0.001266
	3	0.001096
	4	0.001295
L4	1	0.001292
	2	0.001949
	3	0.001259
	4	0.00126
L5	1	0.001178
	2	0.001193
	3	0.001379
	4	0.001433
L6	1	0.001708
	2	0.001661
	3	0.001184
	4	0.002027
L7	1	0.00111
	2	0.001462
	3	0.00123
	4	0.001322
L8	1	0.001216
	2	0.001204
	3	0.001284
	4	0.000957
L9	1	0.001212
	2	0.001234
	3	0.001112
	4	0.001108
L10	1	0.001128
	2	
	3	
	4	0.001574

North		
		RMSd (in)
L3N	1	0.00117
	2	0.001477
	3	0.001208
	4	0.001316
L4N	1	0.001113
	2	0.001243
	3	0.001127
	4	0.001047
L5N	1	0.001184
	2	0.00118
	3	0.001246
	4	0.001115
L6N	1	0.001401
	2	0.001208
	3	0.001099
	4	0.001396
L7N	1	0.001438
	2	0.001502
	3	0.001224
	4	0.001122
L8N	1	0.001019
	2	0.001266
	3	0.001096
	4	0.001044
L9N	1	0.001573
	2	0.00118
	3	0.000997
	4	0.001115
L10N	1	0.00147
	2	0.001601
	3	0.001324
	4	0.001439

South		
		RMSd (in)
L11	1	0.001115
	2	0.001323
	3	0.001069
	4	0.001205
L12	1	0.001198
	2	0.001219
	3	0.001093
	4	0.001372
L13	1	0.001587
	2	0.001405
	3	0.001316
	4	0.001652
L14	1	0.001357
	2	0.001345
	3	0.001463
	4	0.001386
L15	1	0.001214
	2	0.001454
	3	0.001034
	4	0.001156
L16	1	0.001084
	2	0.001479
	3	0.001324
	4	0.001106
L17	1	0.001766
	2	0.001938
	3	0.001445
	4	0.001378

North		
		RMSd (in)
L11N	1	0.001006
	2	0.001351
	3	0.001294
	4	0.000933
L12N	1	0.001455
	2	0.001587
	3	0.001198
	4	0.001404
L13N	1	0.001819
	2	0.001093
	3	0.001366
	4	0.001327
L14N	1	0.001099
	2	0.001316
	3	0.001413
	4	0.00126
L15N	1	0.001373
	2	0.001194
	3	0.00119
	4	0.001321
L16N	1	0.001076
	2	0.001468
	3	0.00135
	4	0.001112
L17N	1	0.002213
	2	0.001156
	3	0.001454
	4	0.001288

Based on the taut-string theory equations, cable parameters are identified that have potential to increase understanding of what conditions effects cable vibration amplitude. The parameters are the fundamental cable frequency, ω_1, the cable tension force, *T*, and the cable length, *L*. Figure 6 shows the cable displacement RMS versus fundamental frequency; Figure 7 shows the cable displacement RMS versus cable tension force; and, Figure 8 shows the cable displacement RMS versus cable length.

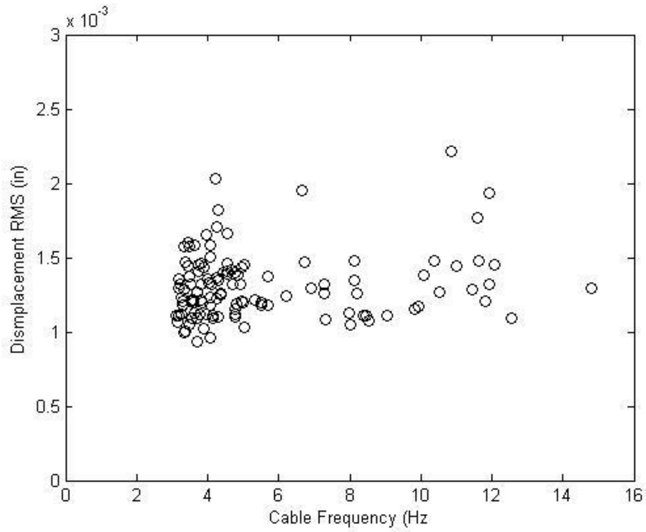


Figure 6. Displacement RMS vs. Frequency

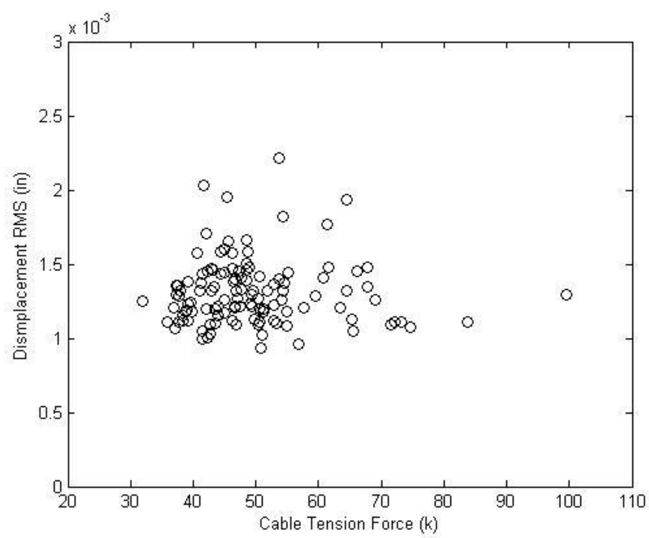


Figure 7. Displacement RMS vs. Tension Force

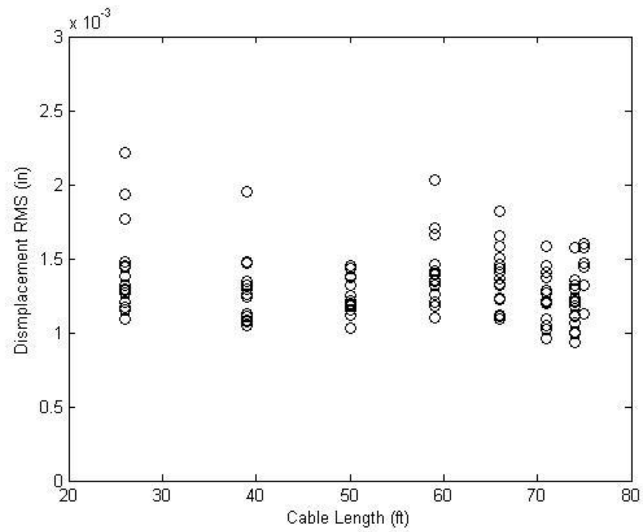


Figure 8. Displacement RMS vs. Cable Length

The figures above do not seem to show any specific trends that would influence which cables have the highest amplitude vibration. Although there are only a limited number of data points for the higher frequency and higher tension cables, there is no apparent relationship between changes in either parameter. Looking at Figure 8, all of the data is located around the average RMS value of 0.0013 inches. A few outliers exist, but 73% of the RMS values are within ±0.0002 inches of the average. Calculating correlation coefficients for each of the parameters, cable frequency, tension force and cable length, against the displacement RMS reveals correlation coefficients of 0.1607, -0.0136 and -0.1684 respectively. Values close to zero represent very low correlation between each of these parameters and the displacement RMS values. From the results of this analysis, the displacement RMS is not influenced by the cable vibration frequency, cable tension force or cable length.

CONSTRUCTION PHASE RESULTS

Due to the importance of the Arrigoni Bridge to the surrounding areas of Middletown and Portland, CT, extensive renovations are currently underway to improve its integrity. Data was collected on October 24, 2011, during a phase of the construction, to look at construction forces and to determine changes in the system behavior. During this stage of the construction, the south deck was removed from cable sets L2 to L10, encompassing approximately half of the south span. The pedestrian sidewalk was removed over the entirety of the south span. The two southern lanes were closed to traffic, and the two northern lanes had one lane of traffic in each direction. In order to describe the construction scenario, Figures 9 and 10 show pictures that represent the system during the construction monitoring.

The same procedure as previously described is performed to calculate the cable tension forces and the extended results are located in Appendix D. The results of these calculations are in Table 3. During the construction phase, different accelerometers are used. Twelve 5g accelerometers are used to collect the data and their specifications and calibration information can be found in Appendix B.

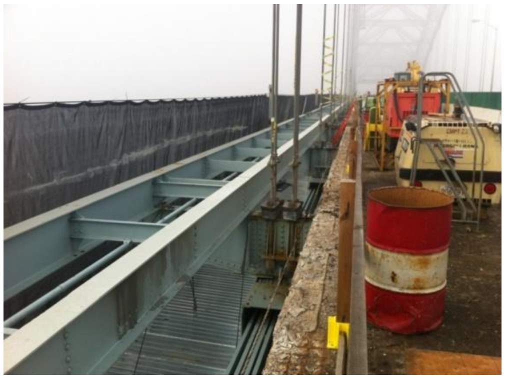


Figure 9. Construction Phase Picture

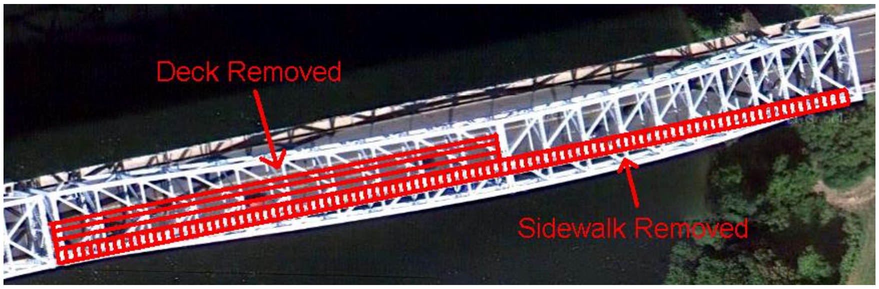


Figure 10. Construction Scenario

Table 4. South Deck Removed Cable Tension Forces

Cable	1	2	3	4
L2				
L3	33.22	33.87	32.39	58.99
L4	38.02	33.07	40.06	38.45
L5	32.10	32.10	33.33	34.51
L6	32.80	37.50	27.93	31.27
L7	34.96	30.09	29.72	36.36
L8	34.50	21.78	25.27	37.53
L9				
L10				
L11	29.45	34.33	32.59	42.59
L12	40.80	37.09	38.86	34.93
L13	34.86	49.49	38.09	40.08
L14	30.03	37.04	38.42	34.80
L15	39.85	38.03	37.48	33.40
L16	43.51	42.60	52.84	48.27
L17	51.01	66.40	54.56	37.33
L18				

Cable	1	2	3	4
L2N				
L3N	42.84	58.93	60.62	62.69
L4N	74.06	41.13	66.83	57.85
L5N	52.40	58.15	40.33	39.13
L6N	46.21	55.60	47.33	41.35
L7N	41.91	45.45	53.21	42.01
L8N	47.75	47.37	47.75	39.43
L9N	43.32	40.17	43.45	53.50
L10N	46.17	47.60	47.08	46.82
L11N	46.98	43.32	37.82	50.92
L12N	49.00	46.63	46.39	51.04
L13N	54.19	43.99	51.87	46.36
L14N	44.49	54.05	44.39	41.16
L15N	51.12	50.58	40.73	41.79
L16N	60.59	41.83	70.36	76.89
L17N	49.33	51.72	66.83	59.34
L18N				

During the construction monitoring, there was not safe access to cable sets L9 and L10 on the south side of the span. Because of this, data was unable to be collected and tension forces could not be estimated for these cables. As in the original testing, the excitation wasn't high enough to be able to determine force measurements for cables L2, L2N, L18 and L18N. To measure these forces, a hammer could be used to excite the cables to measure the resonant frequencies for each of these cables.

In order to more fully understand how the behavior differs between the two monitoring campaigns, individual comparisons of all the cable forces are made. The comparison of every cable that could be safely measured is included for the South cables in Figure 11 and the North cables in Figure 12. South Deck Removed refers to the construction monitoring that occurred on October 24, 2011, whereas Original refers to the initial measurements made on March 8, 2011.

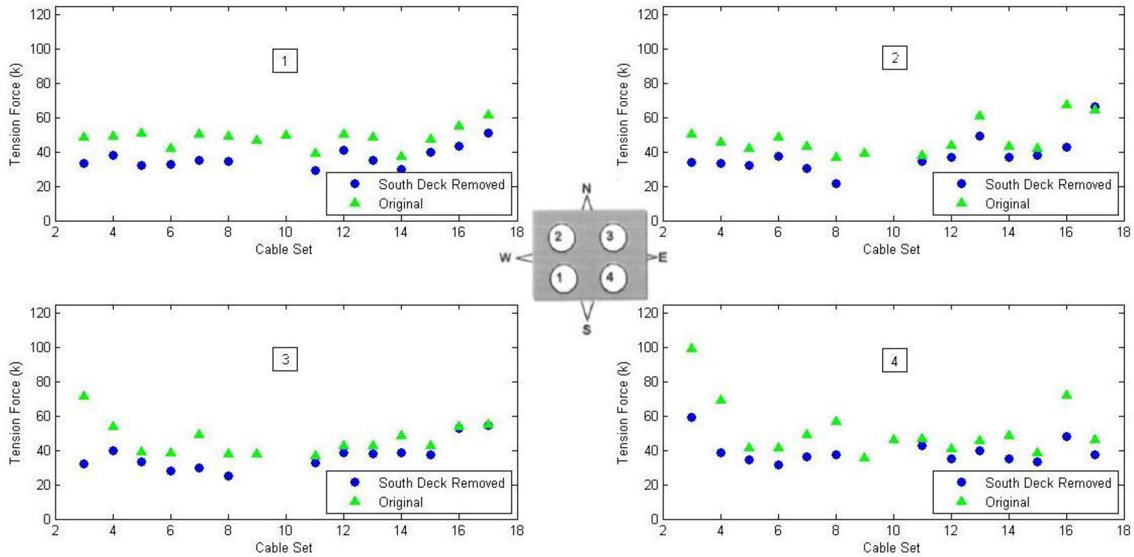


Figure 11. Comparing South Cable Forces

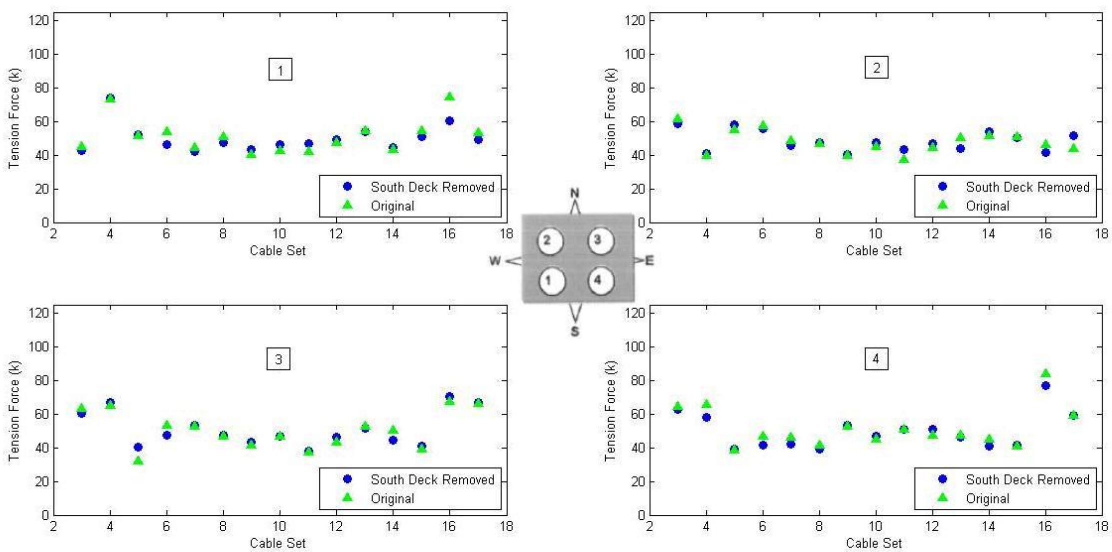


Figure 12. Comparing North Cable Forces

Looking at the South cables in Figure 11, it is evident that the forces in these cables have changed between the two sets of data. The average force reduction for cables L3 to L8 is 16.11 kips, whereas the average force reduction for cables L11 to L17 is 8.01 kips. Generally, the force reduction is larger in cables L3 to L8 because they are directly located where the decking has been removed; hence, it is expected that these cables would have the largest force reduction.

Some force reduction in cables L11 to L17 is expected due to how loads propagate within a system, as well as force redistribution as the system is modified during construction. The sidewalks were removed for both cables L3 to L8 and L11 to L17, whereas the deck was only removed for cables L3 to L8, which accounts for the different force reduction in each half of the cables on the South side span.

Regarding the North cables in Figure 12, the majority of the cables only change a very small amount in their tension forces. The average force change is +0.59 kips, which results in a force change of 1.2% on average. The cable tension forces on the North side do not change much, because they are far away from where the deck is removed and thus do not largely contribute to the load carrying of the southern deck. Some of the cables, such as L5N-3, added more tension force (+8.38 kips) during the construction phase. The forces are redistributing within the cable sets because the other three cables in the set were reduced by 2.42, 2.98 and 4.11 kips. These three reductions sum to 9.51 kips, which means that the cable set's force is reduced by 0.93 kips. Force redistribution within cables accounts for why the cables on the North side have changed, ultimately due to small fluctuations in the system as a whole.

The construction monitoring is very helpful in determining how the system acts when significant changes are made to the system, such as a large portion of the southern decking being completely removed. The effects of this type of change are localized, as would be expected by the design assumptions for this type of bridge.

CONCLUSIONS

The goal of this project was to determine cable tension forces for the suspender cables of the Arrigoni Bridge. A mathematical model incorporating taut-string theory was used to simplify the analysis procedure. An innovative means to use the first four measured natural frequencies of the cable is presented and used in this study to provide a measure of redundancy. The cable tension forces were determined for two scenarios, original and construction phase monitoring. During the original testing, the initial values for all of the cables were determined and the forces and force variability were discussed. In the construction phase testing, it was apparent that the system changes are strongly localized for the removal of the South deck that was tested. The cables closest to the deck removal were most affected, and the North side cables were negligibly affected by the system changes. The variations in the North cables were due to small changes in the system that caused force redistribution within a given cable set. The Arrigoni Bridge suspender cables' tension force has been adequately measured using taut-string theory to model the cable behavior and acceleration data of the out-of-plane motion of the cables. Cable displacement RMS was also examined and it was found that the three test parameters, cable frequency, tension force and cable length did not have any observable relationship with the displacement RMS.

REFERENCES

Irvine, Max H. *Cable Structures*. Cambridge, Massachusetts: MIT Press, 1981.

Martyna, Roman. "Record of Electromagnetic Examination of Suspender Cables." *ConnDOT Internal Report on Arrigoni Bridge*. (2007).

Bendat, Julius S., Piersol, Allen G. *Random Data: Analysis and Measurement Procedures*. New York City: John Wiley & Sons, 2000.

Appendix A – Consideration of Bending Stiffness

This section details the theoretical background for analyzing cables including bending stiffness of the cables. This problem was explored in detail to try to involve higher order modes and shorter cables to try to see significant changes in the force determination using bending stiffness. As stated previously in the report, the inclusion of bending stiffness made little to no change on the values with a maximum of about 2% change on the higher order modes for the shorter cables. This is due to the relatively small cross-sectional area of 0.01351 ft^2. Due to negligible contribution, the effects of bending stiffness were ignored in the main report. It should be noted, however, that the simple taut-string solution provides an upper limit solution to the problem of cable tension estimation.

To begin, a uniform flat-sag cable anchored on supports is shown in Figure A1 below.

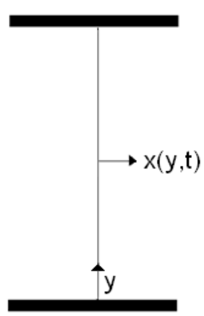


Figure A1. Coordinate System

The nondimensional equation of motion for the in-plane transverse cable motion of vertical cables is given in the Irvine book:

$$w(x,t) + cw(x,t) + \frac{1}{\gamma^2\pi^2}w''''(x,t) - \frac{1}{\pi^2}w''(x,t) = 0 \qquad \text{(A1)}$$

Simplifying the equation of motion, Equation A1, since no damping or sag is assumed:

$$w(x,t) + \frac{1}{\gamma^2\pi^2}w''''(x,t) - \frac{1}{\pi^2}w''(x,t) = 0 \qquad \text{(A2)}$$

Using a Galerkin method, the motion of the cable may be computed using a finite series approximation where the function w(x,t) is given an assumed mode approximation such as:

$$w(x,t) = \sum_{j=1}^{m} \varphi_j(x) q_j(t) \tag{A3}$$

Where $q_j(t)$ are the generalized displacements and the $\varphi_j(x)$ are a set of shape functions that are continuous with piecewise continuous slope and that satisfy the geometric boundary conditions:

$$\varphi_j(0) = \varphi_j(1) = 0$$

A sine series may be used for the shape functions, $\varphi_j(x)$, as follows:

$$\varphi_j(x) = sin(\pi jx), \; j = 1, 2, \ldots, m \tag{A4}$$

Substituting the shape functions into Equation A2 and simplifying results into a matrix form:

$$M\ddot{q} + Kq = 0 \tag{A5}$$

with mass M = [m_{ij}] and stiffness K = [k_{ij}] matrices. Equations A6, A9 and A11 all describe the nondimensional equations to determine the mass and stiffness matrices of the system. An expression for the mass matrix, m_{ij}, will be determined first:

$$m_{ij} = \int_0^1 \varphi_i(x) \varphi_j(x)\, dx = \int_0^1 sin(\pi ix)\, sin(\pi jx)\, dx \tag{A6}$$

$If\ i = j,$

$$m_{ij} = \int_0^1 \sin^2(\pi ix)\, dx = \frac{x}{2} - \frac{\sin(2\pi ix)}{4\pi i}\Big|_0^1 = \frac{1}{2}$$

$If\ i \neq j,$

$$m_{ij} = \frac{j\sin(\pi ix)\cos(\pi jx) - i\cos(\pi ix)\sin(\pi jx)}{\pi i^2 - \pi j^2}\Big|_0^1 = 0$$

$Thus,$

$$m_{ij} = \frac{1}{2}\delta_{ij} \tag{A7}$$

where δ_{ij} is the Kronecker Delta such that when i = j, δ_{ij} = 1 and i ≠ j, δ_{ij} = 0.

The stiffness matrix can be shown by the following equation:

$$k_{ij} = \lambda^2 k_i^{sag} k_j^{sag} + k_{ij}^{tension} + k_{ij}^{bending} \tag{A8}$$

We know from the assumption of no sag that $\lambda^2 = 0$ and so the first term does not play a role in the stiffness determination. Now, $k^{tension}$ and $k^{bending}$ will both be determined using their separate Equations A9 and A11. For the axial stiffness of the cable:

$$k_{ij}^{tension} = \int_0^1 \varphi_i'(x)\,\varphi_j'(x)\,dx \tag{A9}$$

$Where\ \varphi_i'(x) = \pi i \cos(\pi i x)\ \ and\ \varphi_j'(x) = \pi j \cos(\pi j x)$

$$k_{ij}^{tension} = \int_0^1 \pi i \cos(\pi i x)\,\pi j \cos(\pi j x)\,dx$$

$If\ i = j,$

$$k_{ij}^{tension} = \pi^2 i^2 \int_0^1 \cos^2(\pi i x)\,dx = \pi^2 i^2 \left(\frac{x}{2} + \frac{\sin 2\pi i x}{4\pi i}\right)\Big|_0^1 = \frac{1}{2}\pi^2 i^2$$

$If\ i \neq j,$

$$k_{ij}^{tension} = \pi^2 ij \int_0^1 \cos(\pi i x)\cos(\pi j x)\,dx$$

$$k_{ij}^{tension} = \pi^2 ij \left(\frac{\sin x(\pi i - \pi j)}{2\pi(i-j)} + \frac{\sin x(\pi i + \pi j)}{2\pi(i+j)}\right)\Big|_0^1 = 0$$

$Thus,$

$$k_{ij}^{tension} = \frac{1}{2}\pi^2 i^2 \delta_{ij} \tag{A10}$$

For the bending stiffness of the cable:

$$k_{ij}^{bending} = \frac{1}{\gamma^2}\int_0^1 \varphi_i''(x)\varphi_j''(x)dx \tag{A11}$$

$Where\ \varphi_i''(x) = -\pi^2 i^2 \sin(\pi i x)\ \ and\ \varphi_j''(x) = -\pi^2 j^2 \sin(\pi j x)$

$$k_{ij}^{bending} = \frac{1}{\gamma^2}\int_0^1 \left(-\pi^2 i^2 \sin(\pi i x)\right)\left(-\pi^2 j^2 \sin(\pi j x)\right)dx$$

$If\ i = j,$

$$k_{ij}^{bending} = \frac{1}{\gamma^2}\pi^4 i^4 \int_0^1 \sin^2(\pi i x)\,dx = \frac{1}{2}\frac{\pi^4 i^4}{\gamma^2}\delta_{ij}$$

$If\ i \neq j,$

$$k_{ij}^{bending} = \frac{1}{\gamma^2}\pi^4 i^2 j^2 \int_0^1 sin(\pi i x)\,sin(\pi j x)\,dx = 0$$

$Thus,$

$$k_{ij}^{bending} = \frac{1}{2}\frac{\pi^4 i^4}{\gamma^2}\delta_{ij} \tag{A12}$$

$Where\ \frac{1}{\gamma^2} = \frac{EI}{HL^2}$, E is the Modulus of Elasticity, I is the area moment of inertia, H is the tension force in the cable and L is the length of the cable. Combining Equations A10 and A12 yields the stiffness matrix Equation A13:

$$k_{ij} = \frac{1}{2}\pi^2 i^2 \delta_{ij} + \frac{1}{2}\frac{\pi^4 i^4}{\gamma^2}\delta_{ij} \tag{A13}$$

Now that expressions for m_{ij} and k_{ij} have been determined (Equations A7 and A13), this information can be used to solve the eigenvalue problem that determines the natural frequencies of a given cable.

$$m_{ij}q + k_{ij}q = 0$$

The solution of this problem can be performed using the characteristic equation for eigenvalue problems:

$$\det\ k_{ij} - \omega_n^2 m_{ij}\ = 0\ solve\ for\ \omega_n \tag{A14}$$

$Where\ \omega_n = \frac{\omega_n L}{\frac{H}{m}}$ and m is the mass per unit length of the cable material. This equation can be used to determine the natural frequencies, ω_n, of the cable, if ω_n is known.

Appendix B – Accelerometer Calibration Information

Technical Specifications	
Channels	4 to 64, Expandable in multiples of 4
Hardware Accuracy	± 0.2% (2% for Strain Transducers)
Sample Rates	Max 500 Hz (Internal over-sampling rate is 19.5-312 KHz)
Max Test Lengths	21 minutes at 100 Hz. 128K samples per channel maximum test length
Gain Levels	1, 2, 4, 6, 16, 32, 64, 128
Digital Filter	Fixed by selected sample rate
Analog Filter	200 Hz, -3db, 3rd order Bessel
Max. Input Voltage	10.5 VDC
Power	9.6V NiMH rechargeable battery (Programmable low-power sleep mode)
Alternative Power	9-48 VDC input
Excitation Voltages Standard: LVDT/Other	 5 Volts DC 5.5 Volts DC
A/D Resolution	0.3uV bit (24-Bit ADC)
PC Requirements	Windows 2000 or higher
PC Interface	Wi-Fi Ethernet 802.11b: 10/100 Mbps
Auto Zeroing	Sensor automatically zero before each test
Enclosures	Aluminum splash resistant
Sensor Connections	All aluminum military grade, circular bayonet "snap" lock
Vehicle Tracking	BDI AutoClicker, switch closure detection
Sensors	BDI Intelliducer Strain Transducers Also supports LVDTs, foil strain gages, accelerometers, various DC output sensors Single RS232 serially-interfaced sensor
On-board PC Processor: RAM	 520 MHz Intel XScale PXA270 64MB
Dimensions Base Station: STS 4 Channel Unit:	 10" x 6" x 4" 11" x 3.5" x 3.25"

Figure B1. STS-WiFi Structural Testing System Specifications

Table B1. BDI Accelerometer Specifications

DYNAMIC

							NOTES
Range (g)	±2	±5	±10	±20	±50	±100	
Sensitivity (mV/g) [1]	5.0-9.0	2.4-3.6	1.2-1.8	0.6-0.9	0.24-0.36	0.12-0.18	@5Vdc Excitation
Frequency Response (Hz)	0-150	0-250	0-400	0-600	0-1000	0-1500	±5%
Natural Frequency (Hz)	700	800	1000	1500	4000	6000	
Non-Linearity (%FSO)	±0.5	±0.5	±0.5	±0.5	±0.5	±0.5	
Transverse Sensitivity (%)	<3	<3	<3	<3	<3	<3	<1 Typical
Damping Ratio	0.7	0.7	0.7	0.7	0.7	0.7	
Shock Limit (g)	10000	10000	10000	10000	10000	10000	

GENERAL SPECIFICATIONS

Overall Size	1.95 in X 0.80 in X 0.49 in (49.5 mm X 20.3 mm X 12.4 mm)
Cable Length	10ft (3m) any length available
Housing Material	Aluminum
Circuitry	Full Wheatstone Bridge silicon MEMS with integral temperature compensation
Excitation Voltage (Vdc)	2 - 10
Output Resistance (Ω)	1900 - 6500
Thermal Zero Shift (%FSO/ °C)	±0.060
Thermal Sensitivity Shift (%/ °C)	±0.060
Operating Temperature	-40 to +125
Compensated Temperature (°C)	0 to +50

* All values are typical at +24°C, 100Hz and 5Vdc excitation unless otherwise stated. Measurement Specialies reserves the right to update

Table B2. 50g Accelerometer Calibration Table

Sensor ID	BDI Gauge Factor (g/Vout/Vexcitation)	Calibration Factor (mV/g)
A4022	3344.48	0.299000
A4023	3344.48	0.299000
A4024	3344.48	0.299000
A4025	3355.70	0.298000
A4026	3333.33	0.300000
A4027	3333.33	0.300000
A4028	3389.00	0.295072
A4029	3521.13	0.284000
A4031	3401.30	0.294005
A4040	3205.12	0.312001
A4043	3533.56	0.283001
A4045	3367.00	0.297000

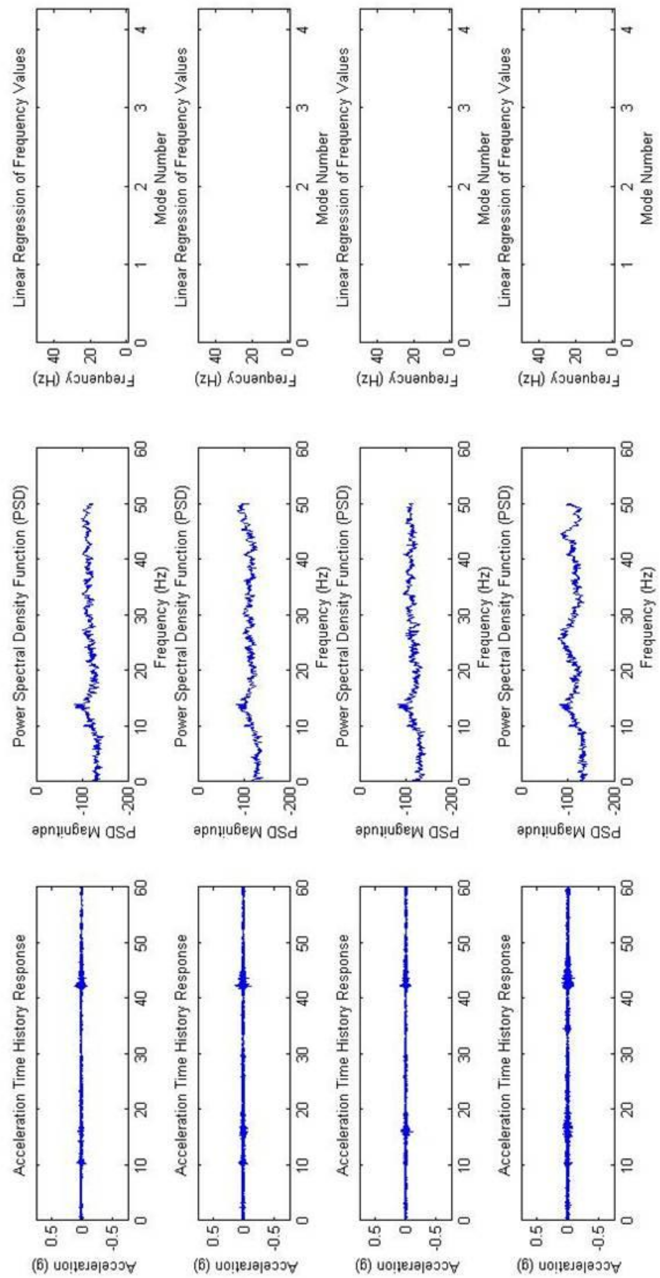
Table B3. 5g Accelerometer Calibration Table

Sensor ID	BDI Gauge Factor (g/Vout/Vexcitation)	Calibration Factor (mV/g)
A2019	355.87	2.8100
A2020	354.61	2.8200
A2021	361.01	2.7700
A2022	350.87	2.8501
A2023	375.93	2.6601
A2024	367.64	2.7201
A2025	378.78	2.6401
A2026	326.79	3.0601
A2027	364.96	2.7400
A2028	358.42	2.7900
A2029	359.71	2.7800
A2030	364.96	2.7400

Appendix C – Original Results – Cable Tension Graphs and Tables

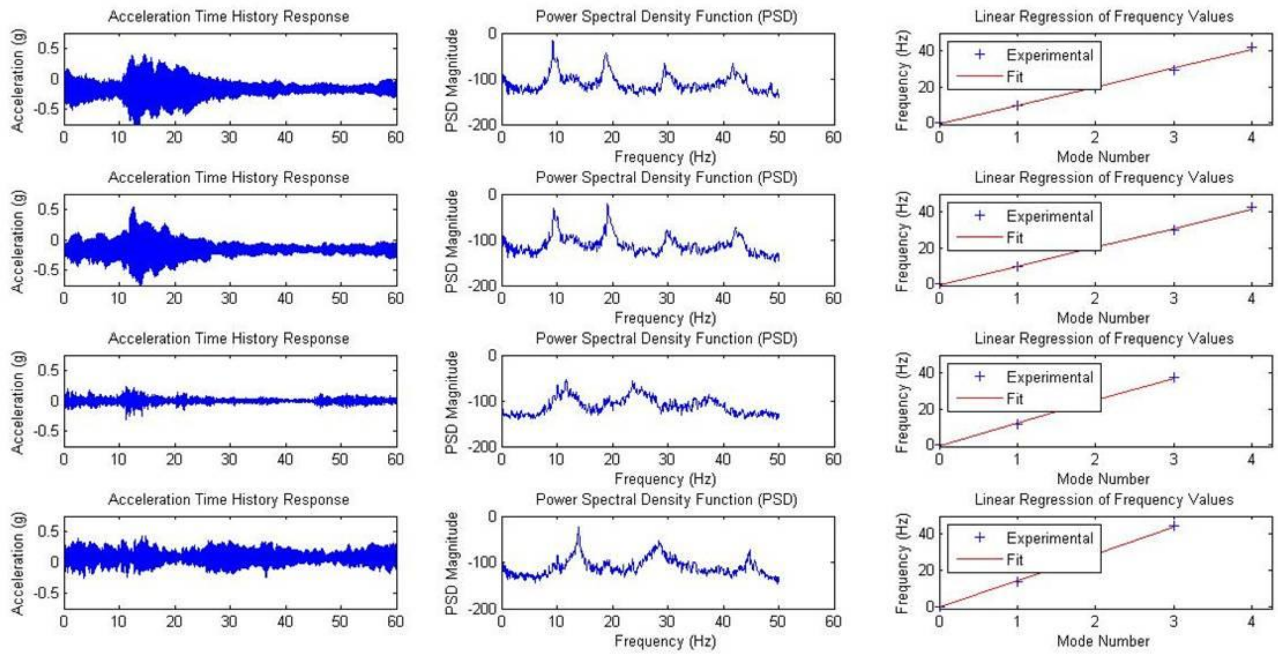
SOUTH SPAN

Cable Set L2



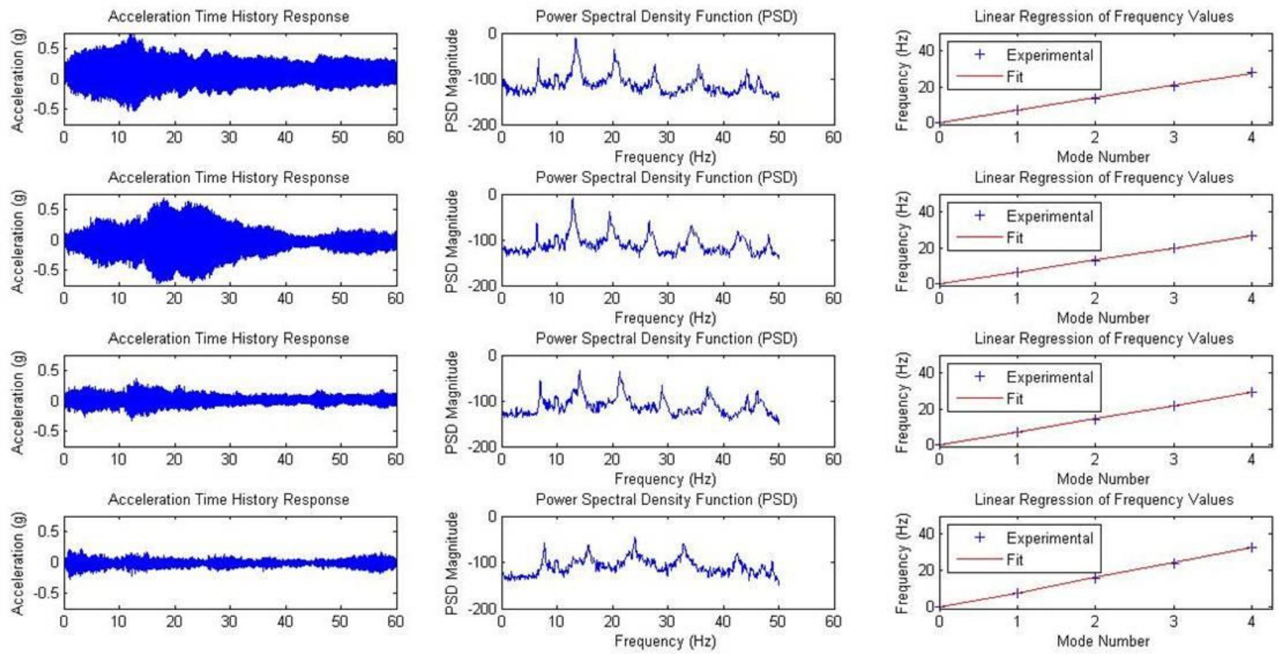
L2	w1 (Hz)	w2 (Hz)	w3 (Hz)	w4 (Hz)	wfit (Hz)	Norm of R	T (k)
1							
2							
3							
4							

Cable Set L3



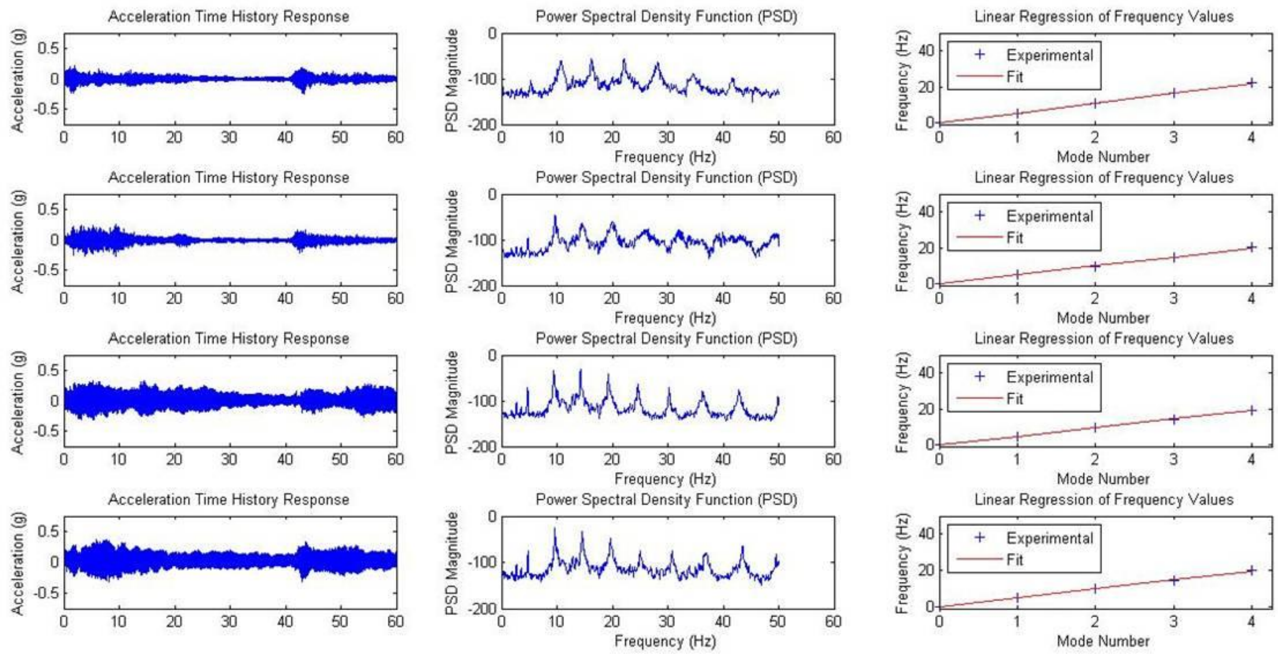
L3	w1 (Hz)	w2 (Hz)	w3 (Hz)	w4 (Hz)	wfit (Hz)	Norm of R	T (k)
1	9.54	18.93	29.54	41.81	10.36	1.88	48.87
2	9.63	19.32	29.93	42.45	10.52	1.88	50.36
3	11.69	23.72	37.80		12.54	1.26	71.61
4	13.94	28.51	44.46		14.79	1.02	99.59

Cable Set L4



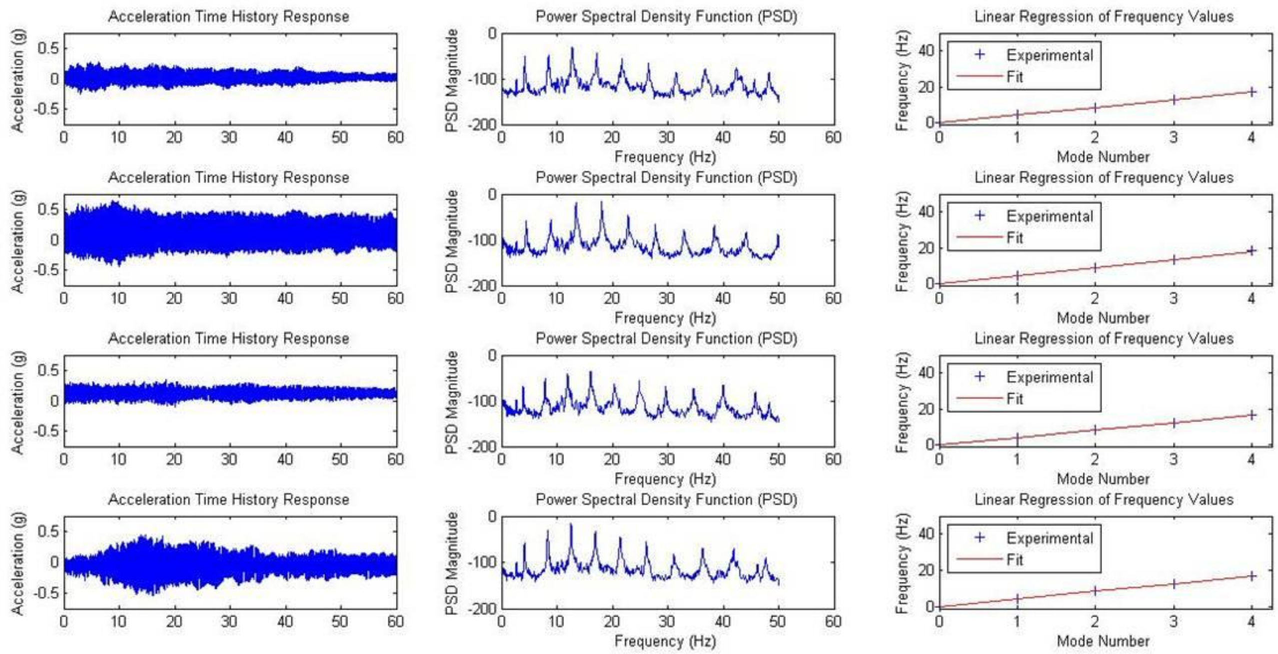
L4	w1 (Hz)	w2 (Hz)	w3 (Hz)	w4 (Hz)	wfit (Hz)	Norm of R	T (k)
1	6.85	13.45	20.64	27.78	6.93	0.36	49.24
2	6.55	13.01	19.81	26.70	6.67	0.29	45.49
3	7.19	14.28	21.57	29.15	7.27	0.29	54.07
4	7.68	15.55	23.92	32.96	8.22	0.88	69.12

Cable Set L5



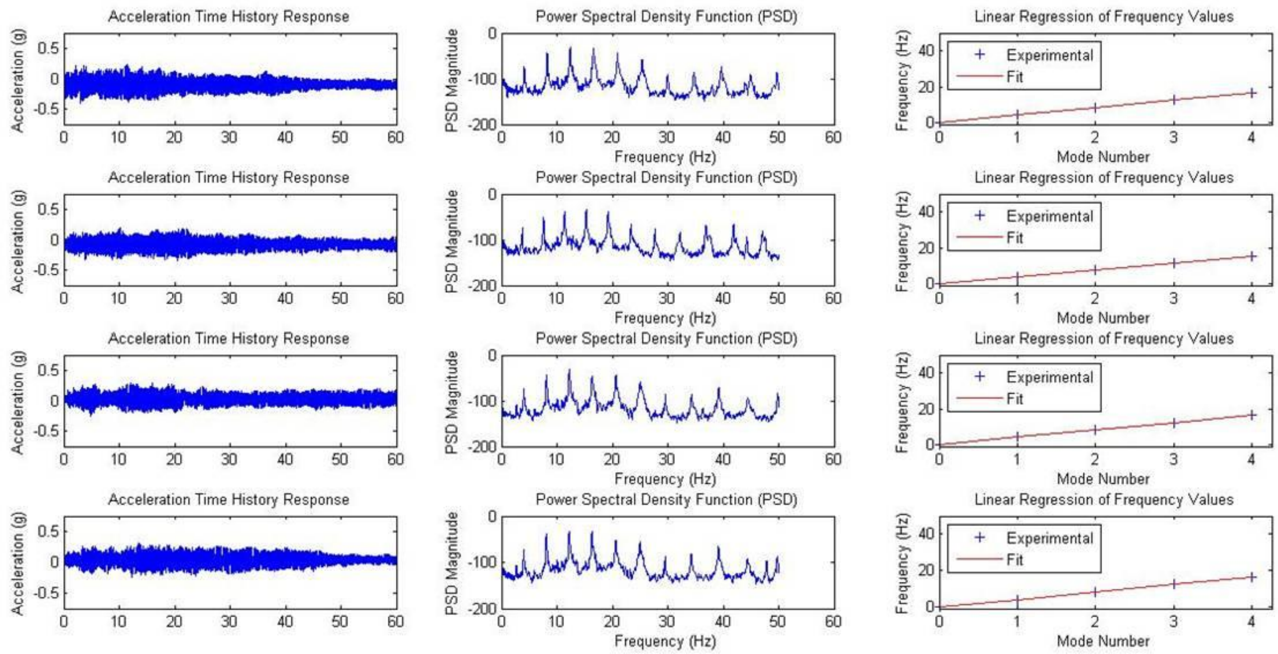
L5	w1 (Hz)	w2 (Hz)	w3 (Hz)	w4 (Hz)	wfit (Hz)	Norm of R	T (k)
1	5.23	10.71	16.29	22.06	5.52	0.32	51.21
2	4.74	9.83	14.67	20.05	5.00	0.33	42.12
3	4.60	9.44	14.23	19.32	4.83	0.26	39.21
4	4.74	9.78	14.72	19.81	4.96	0.18	41.39

Cable Set L6



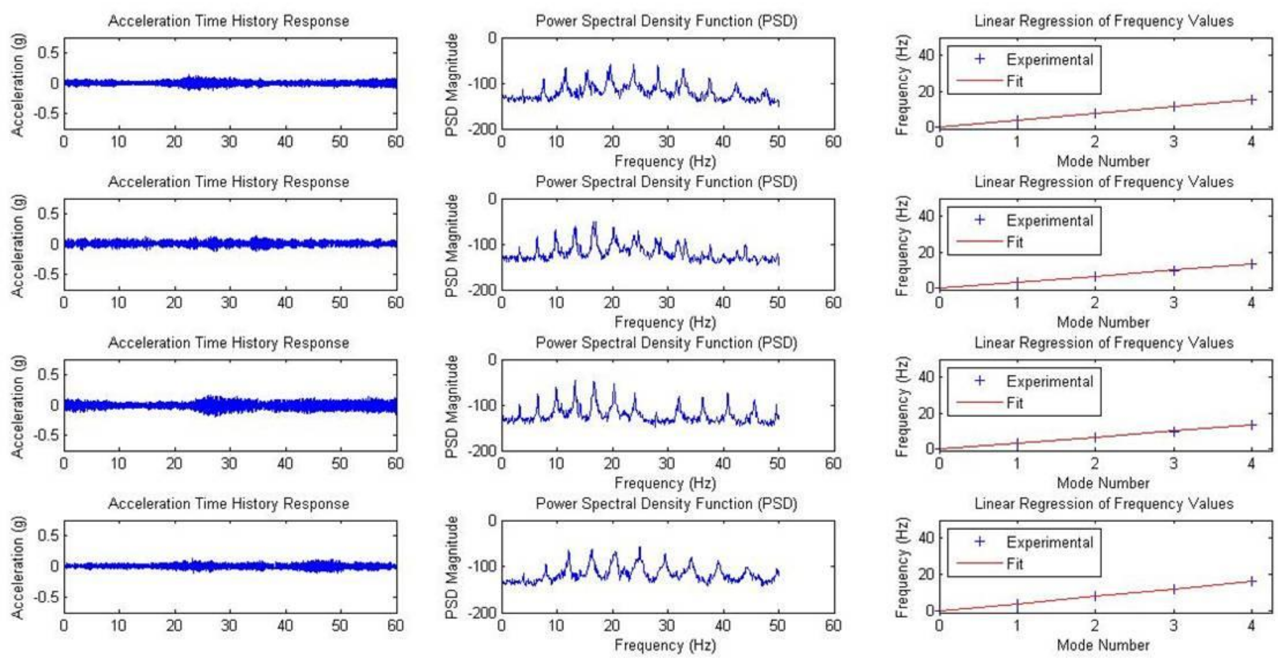
L6	w1 (Hz)	w2 (Hz)	w3 (Hz)	w4 (Hz)	wfit (Hz)	Norm of R	T (k)
1	4.40	8.56	12.76	17.02	4.24	0.12	42.13
2	4.40	8.85	13.60	18.14	4.55	0.20	48.47
3	4.01	8.07	12.18	16.24	4.06	0.05	38.70
4	4.40	8.46	12.57	17.02	4.22	0.22	41.74

<u>Cable Set L7</u>



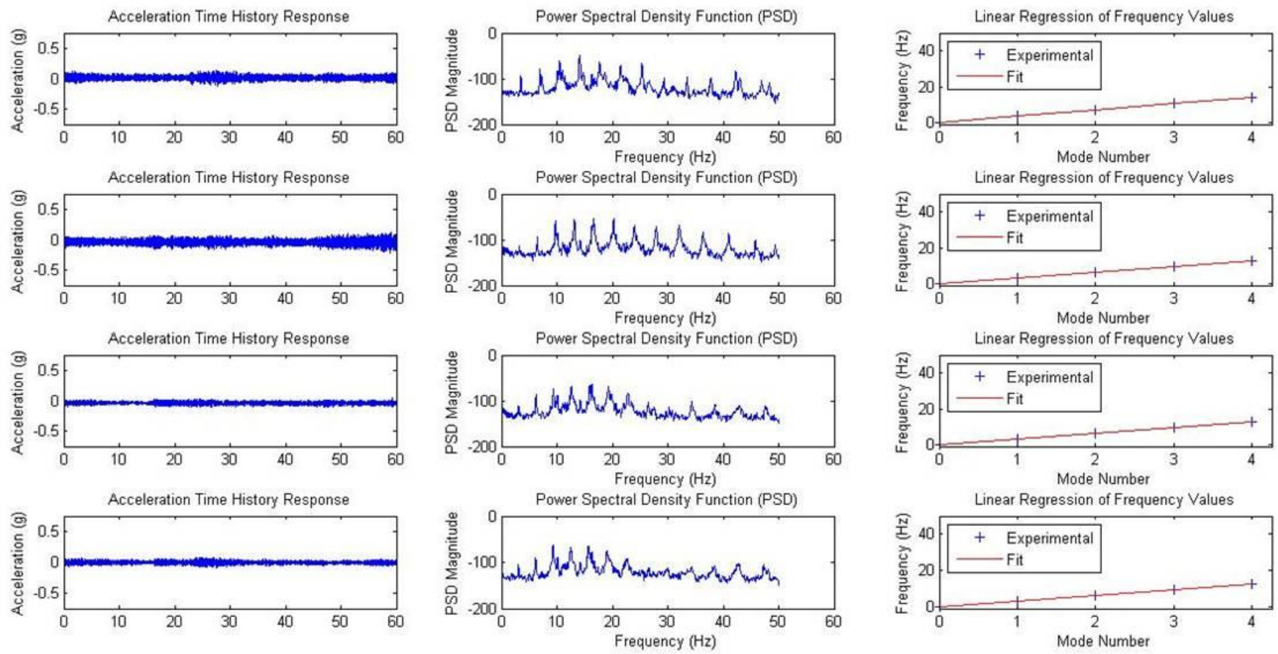
L7	w1 (Hz)	w2 (Hz)	w3 (Hz)	w4 (Hz)	wfit (Hz)	Norm of R	T (k)
1	4.21	8.36	12.57	16.58	4.15	0.11	50.55
2	3.72	7.73	11.44	15.31	3.83	0.13	43.11
3	4.16	8.22	12.32	16.38	4.09	0.05	49.13
4	4.01	8.02	12.23	16.43	4.11	0.16	49.49

Cable Set L8



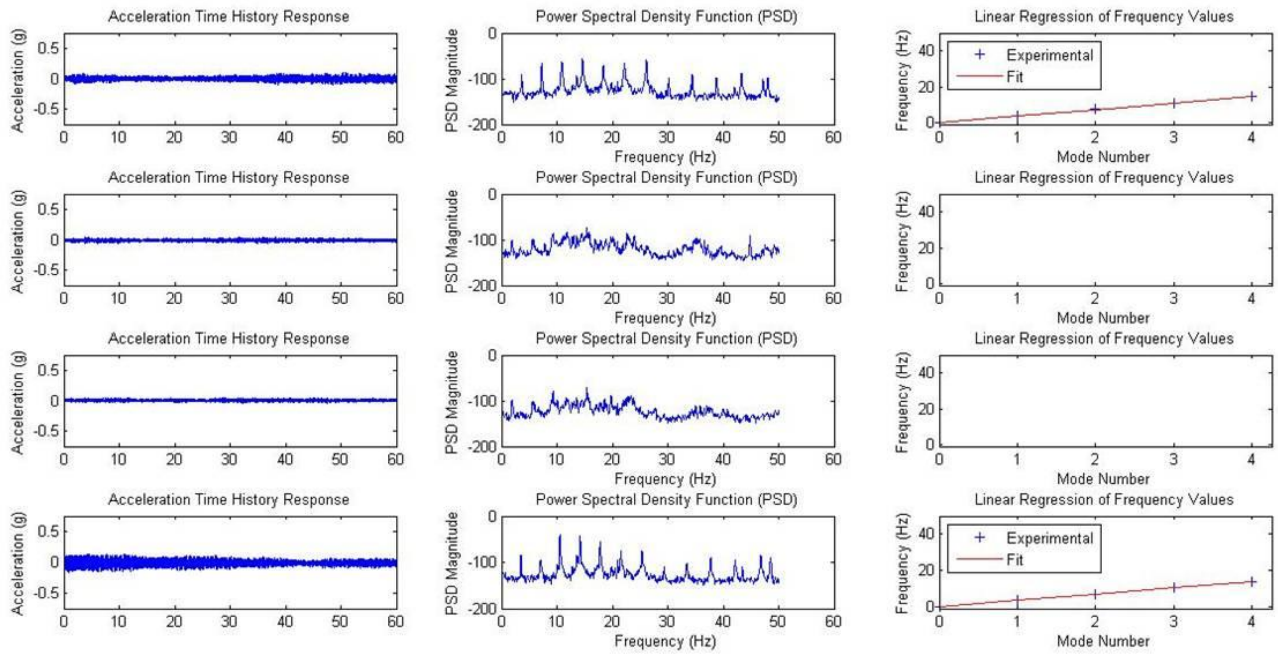
L8	w1 (Hz)	w2 (Hz)	w3 (Hz)	w4 (Hz)	wfit (Hz)	Norm of R	T (k)
1	4.01	7.68	11.54	15.31	3.81	0.15	49.38
2	3.18	6.60	9.78	13.20	3.30	0.13	36.98
3	3.18	6.60	9.83	13.35	3.34	0.17	37.75
4	3.91	7.97	12.13	16.33	4.09	0.19	56.72

Cable Set L9



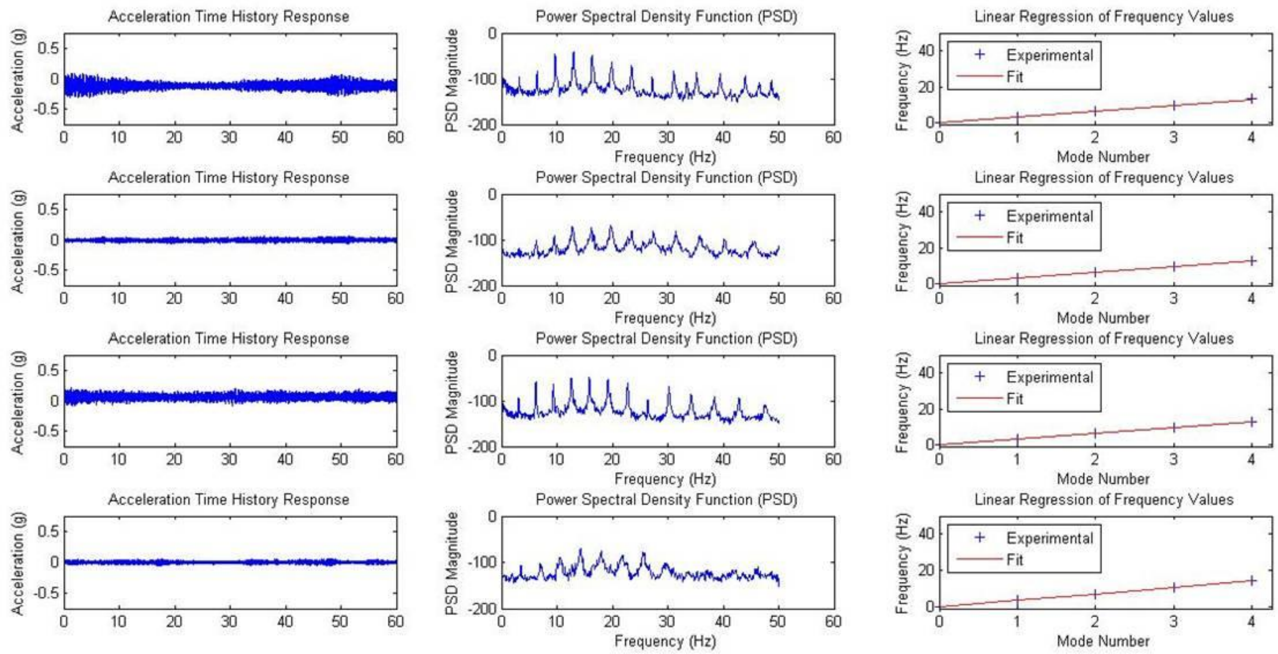
L9	w1 (Hz)	w2 (Hz)	w3 (Hz)	w4 (Hz)	wfit (Hz)	Norm of R	T (k)
1	3.57	7.24	10.56	14.28	3.56	0.17	46.60
2	3.08	6.50	9.78	12.96	3.26	0.15	39.22
3	3.13	6.06	9.63	12.76	3.20	0.29	37.82
4	3.23	6.36	9.34	12.52	3.12	0.12	35.77

Cable Set L10



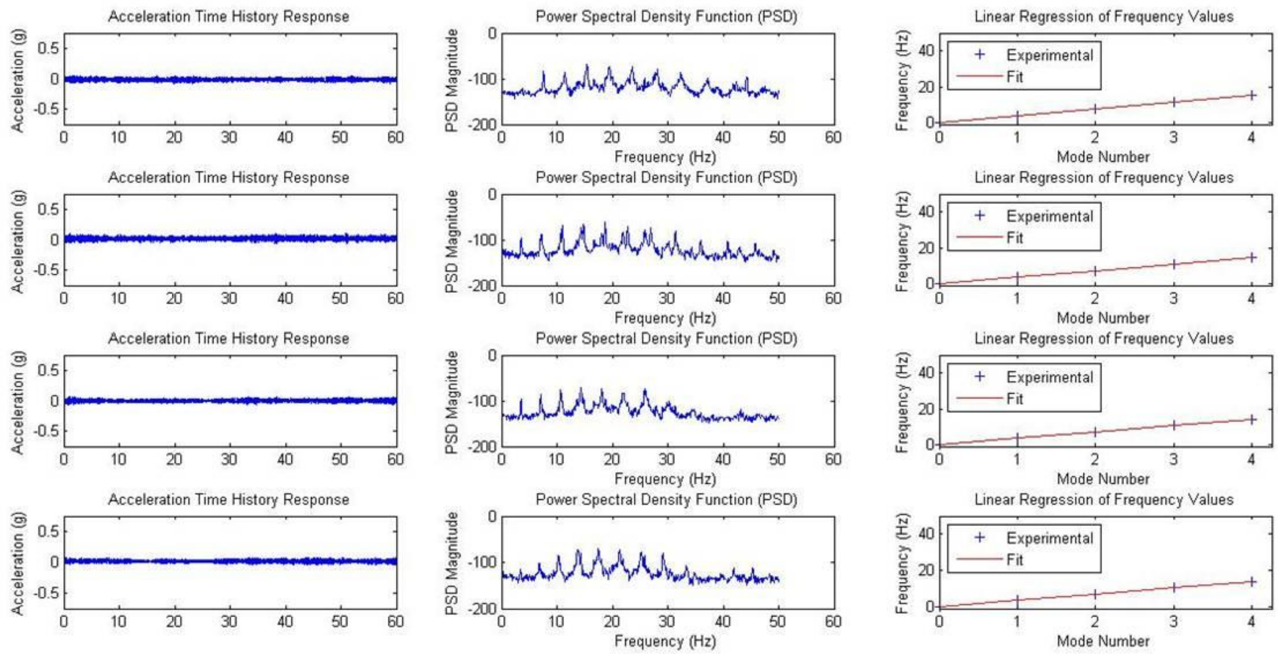
L10	w1 (Hz)	w2 (Hz)	w3 (Hz)	w4 (Hz)	wfit (Hz)	Norm of R	T (k)
1	3.72	7.34	10.81	14.57	3.62	0.14	49.73
2							
3							
4	3.62	7.04	10.51	14.04	3.50	0.09	46.30

Cable Set L11



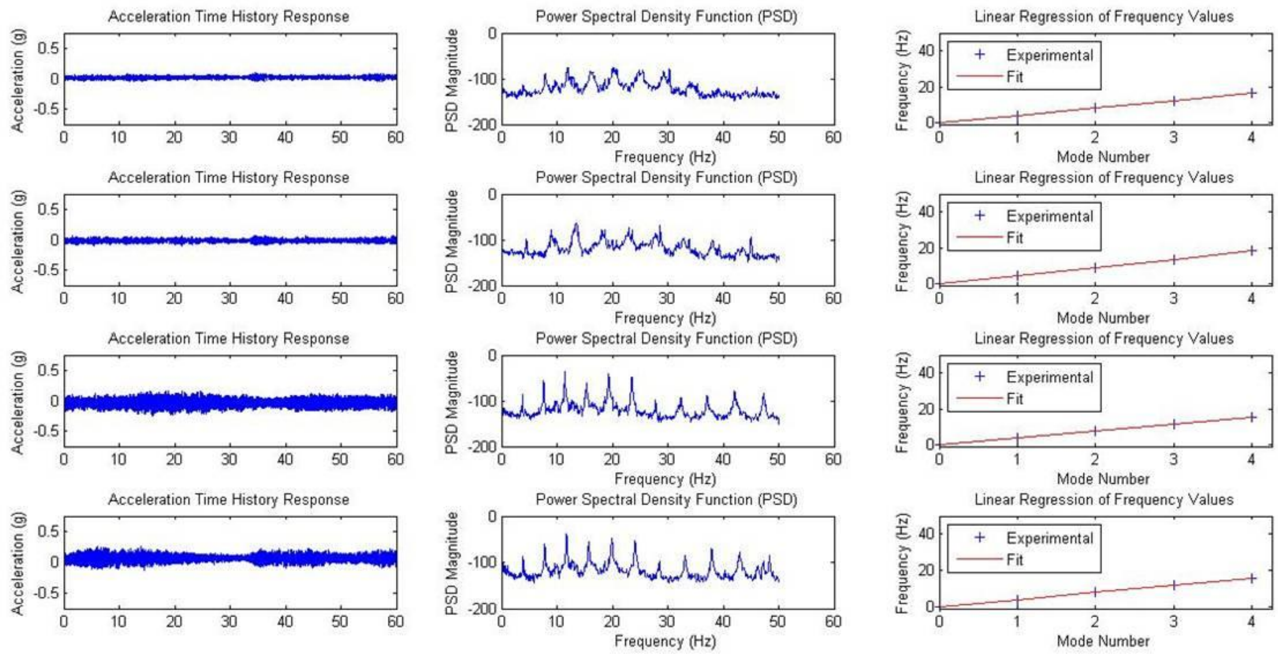
L11	w1 (Hz)	w2 (Hz)	w3 (Hz)	w4 (Hz)	wfit (Hz)	Norm of R	T (k)
1	3.23	6.50	9.63	13.11	3.26	0.15	39.22
2	3.03	6.26	9.49	12.81	3.21	0.16	37.94
3	2.98	6.31	9.49	12.62	3.17	0.15	37.13
4	3.47	7.04	10.47	14.28	3.56	0.20	46.60

Cable Set L12



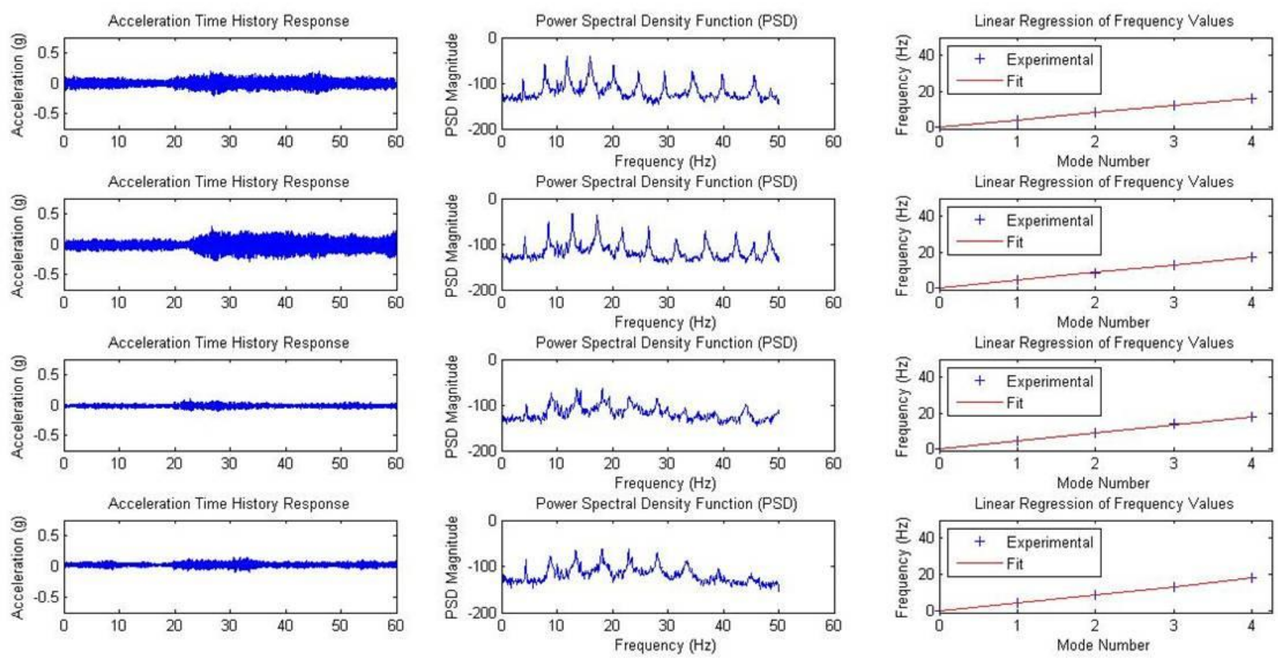
L12	w1 (Hz)	w2 (Hz)	w3 (Hz)	w4 (Hz)	wfit (Hz)	Norm of R	T (k)
1	3.62	7.38	11.35	15.45	3.86	0.31	50.65
2	3.72	7.29	10.91	14.38	3.59	0.13	43.85
3	3.67	7.09	10.81	14.18	3.55	0.16	42.78
4	3.42	6.80	10.42	13.94	3.49	0.14	41.26

Cable Set L13



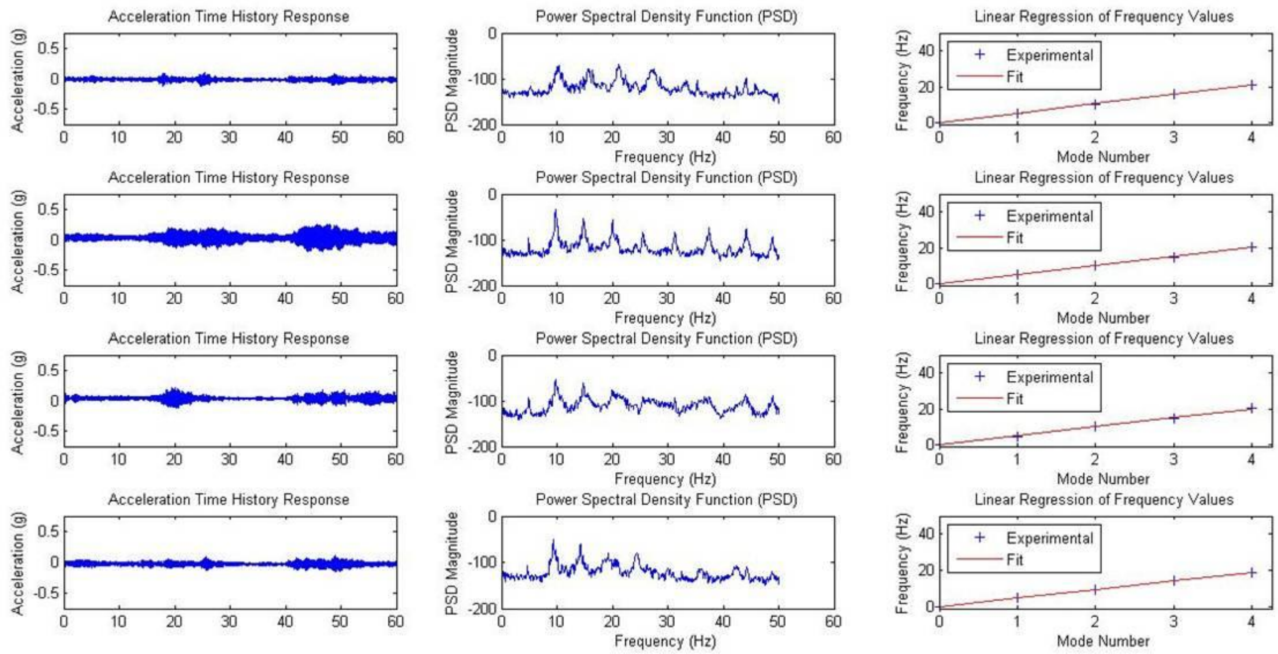
L13	w1 (Hz)	w2 (Hz)	w3 (Hz)	w4 (Hz)	wfit (Hz)	Norm of R	T (k)
1	4.01	8.07	12.03	16.38	4.08	0.21	48.78
2	4.65	9.10	13.40	18.39	4.55	0.33	60.79
3	3.72	7.68	11.35	15.31	3.82	0.15	42.89
4	3.77	7.92	11.74	15.75	3.95	0.17	45.67

Cable Set L14



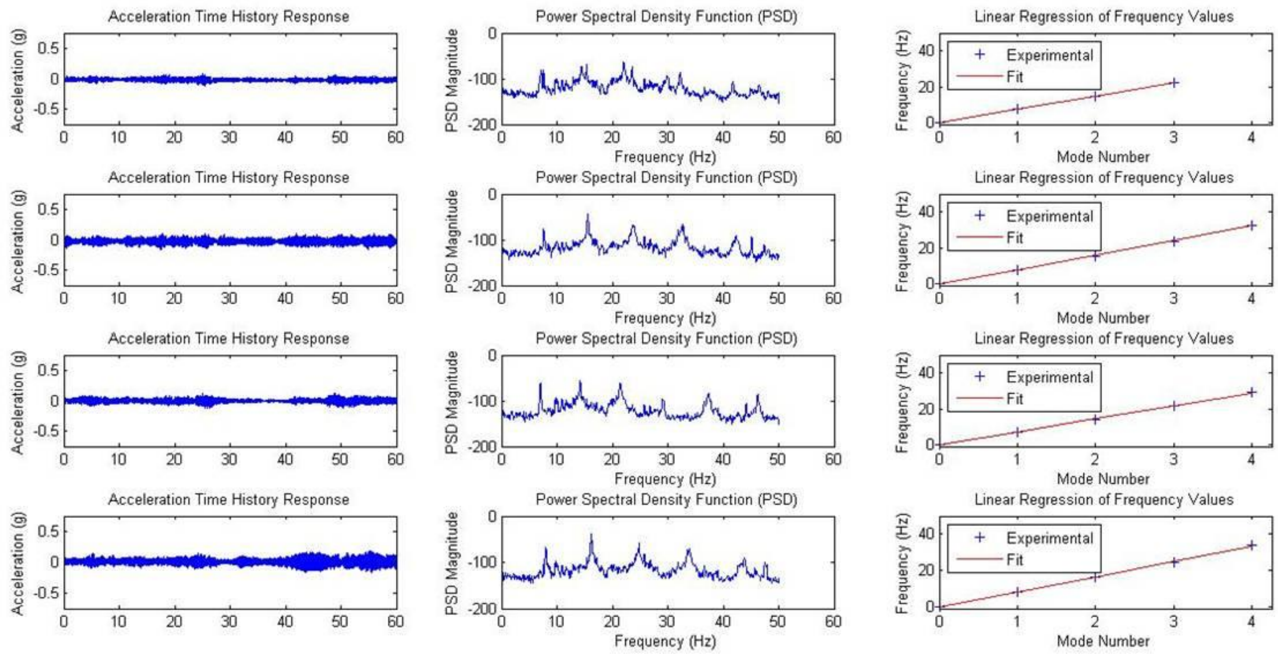
L14	w1 (Hz)	w2 (Hz)	w3 (Hz)	w4 (Hz)	wfit (Hz)	Norm of R	T (k)
1	4.06	8.07	11.84	16.09	4.00	0.21	37.41
2	4.40	8.51	12.72	17.36	4.30	0.28	43.40
3	4.35	8.95	13.69	18.10	4.55	0.20	48.58
4	4.30	8.75	13.30	18.24	4.55	0.38	48.47

Cable Set L15



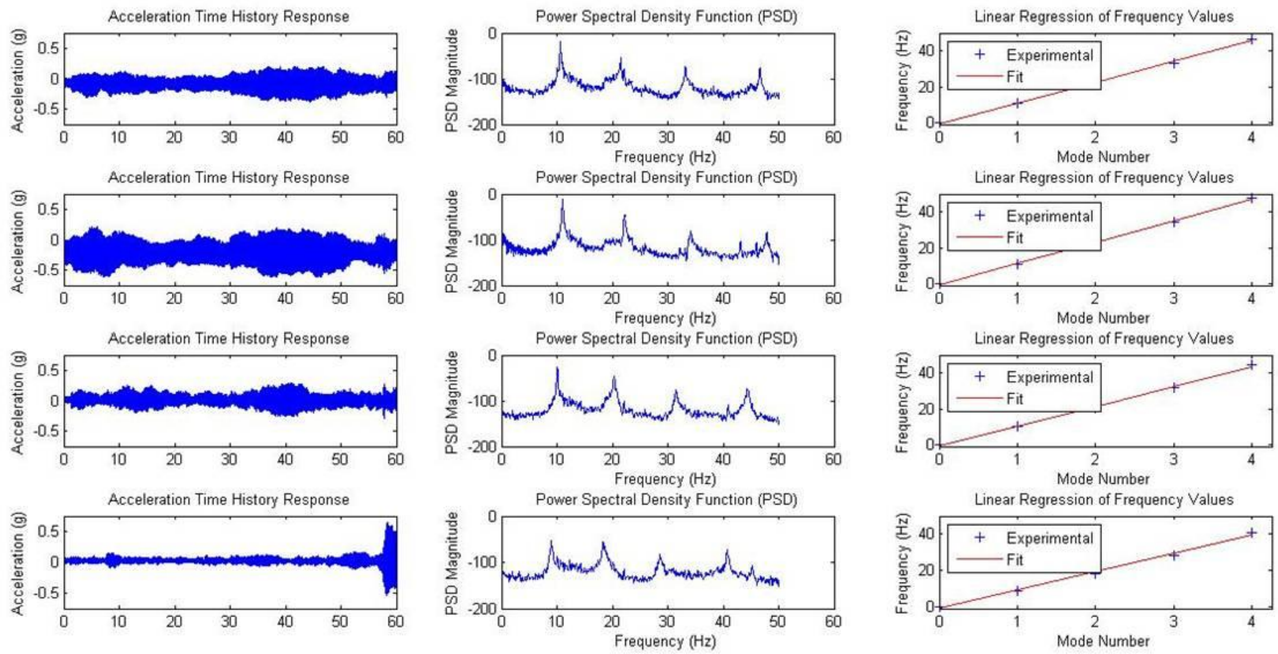
L15	w1 (Hz)	w2 (Hz)	w3 (Hz)	w4 (Hz)	wfit (Hz)	Norm of R	T (k)
1	5.18	10.27	15.80	21.23	5.31	0.28	47.38
2	5.09	9.88	14.87	20.20	5.02	0.27	42.37
3	4.70	9.98	14.87	20.10	5.04	0.29	42.70
4	4.79	9.39	14.33	19.12	4.78	0.15	38.42

Cable Set L16



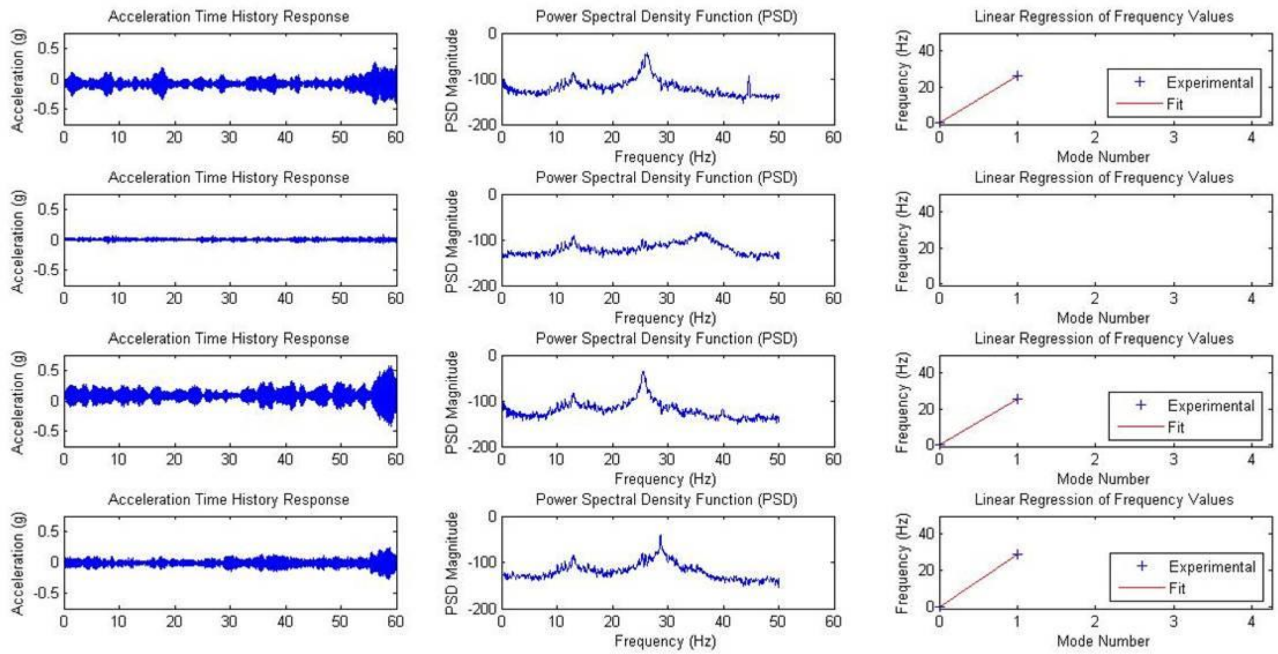
L16	w1 (Hz)	w2 (Hz)	w3 (Hz)	w4 (Hz)	wfit (Hz)	Norm of R	T (k)
1	7.38	14.67	22.01		7.33	0.04	55.03
2	7.63	15.45	23.82	32.57	8.13	0.75	67.72
3	6.99	14.09	21.37	29.20	7.28	0.52	54.22
4	8.12	16.19	24.65	33.70	8.39	0.63	72.11

Cable Set L17



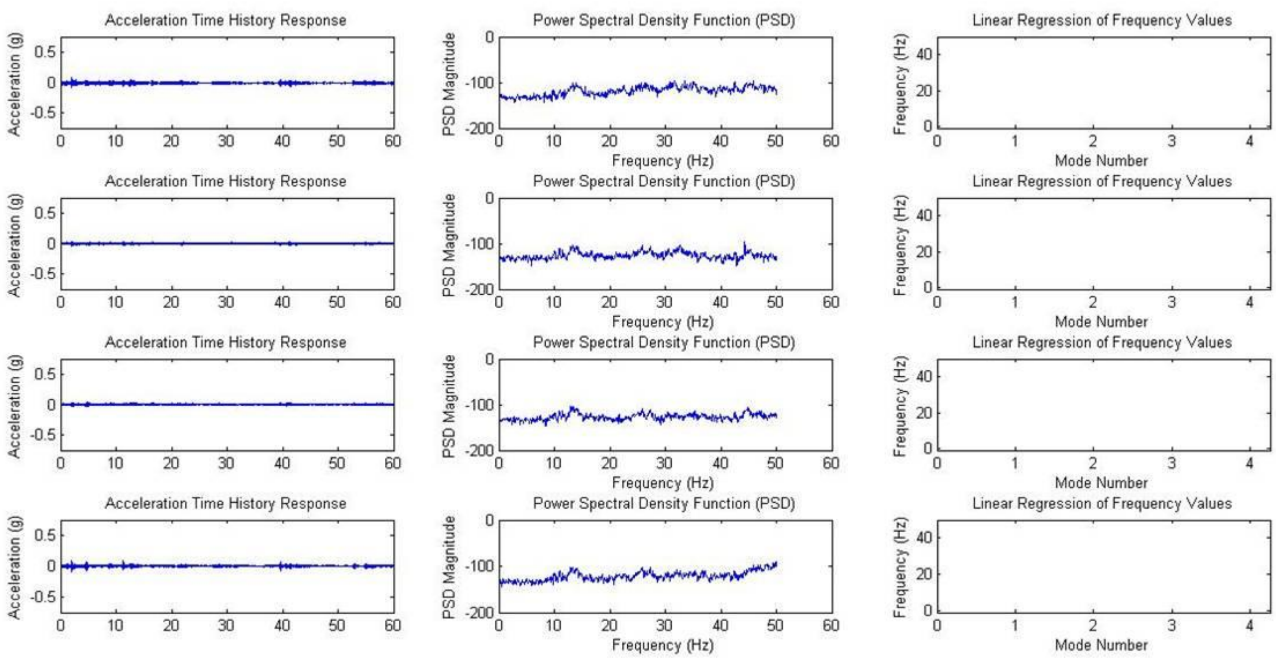
L17	w1 (Hz)	w2 (Hz)	w3 (Hz)	w4 (Hz)	wfit (Hz)	Norm of R	T (k)
1	10.76	21.52	33.35	46.75	11.61	1.77	61.34
2	10.96	22.30	34.38	47.83	11.91	1.56	64.53
3	10.07	20.25	31.59	44.31	11.01	1.77	55.20
4	9.00	18.44	28.56	40.74	10.10	1.95	46.46

Cable Set L18



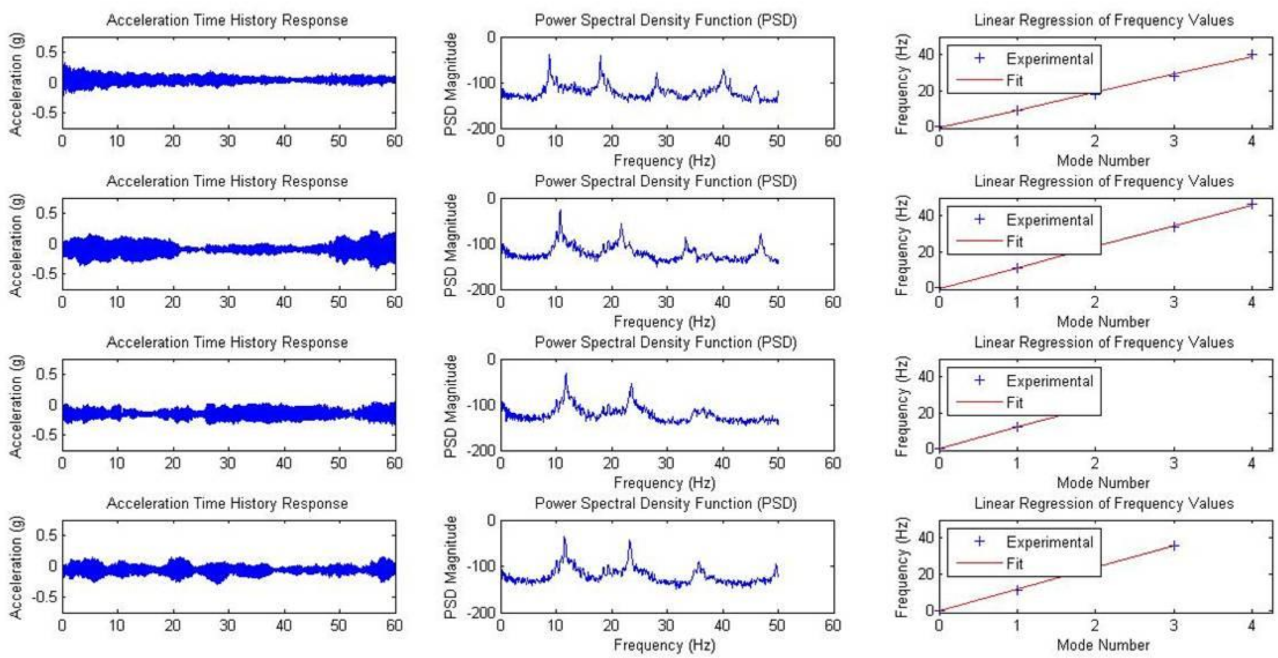
L18	w1 (Hz)	w2 (Hz)	w3 (Hz)	w4 (Hz)	wfit (Hz)	Norm of R	T (k)
1							
2							
3							
4							

Cable Set L2N



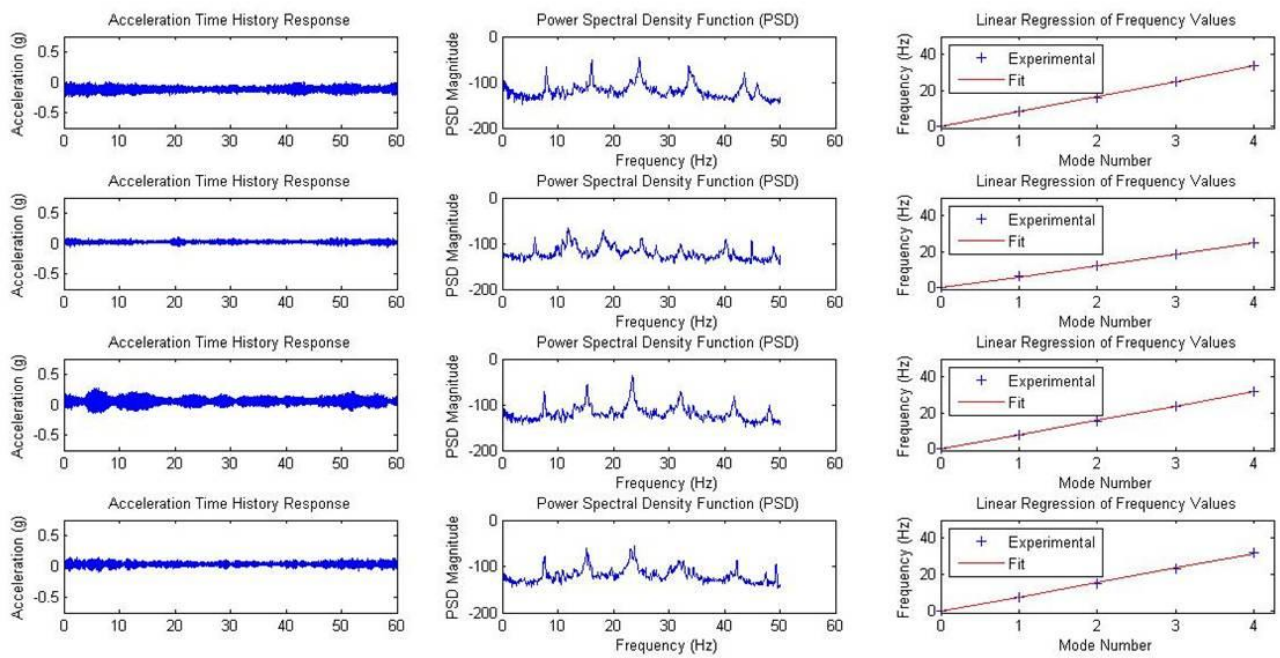
L2N	w1 (Hz)	w2 (Hz)	w3 (Hz)	w4 (Hz)	wfit (Hz)	Norm of R	T (k)
1							
2							
3							
4							

Cable Set L3N



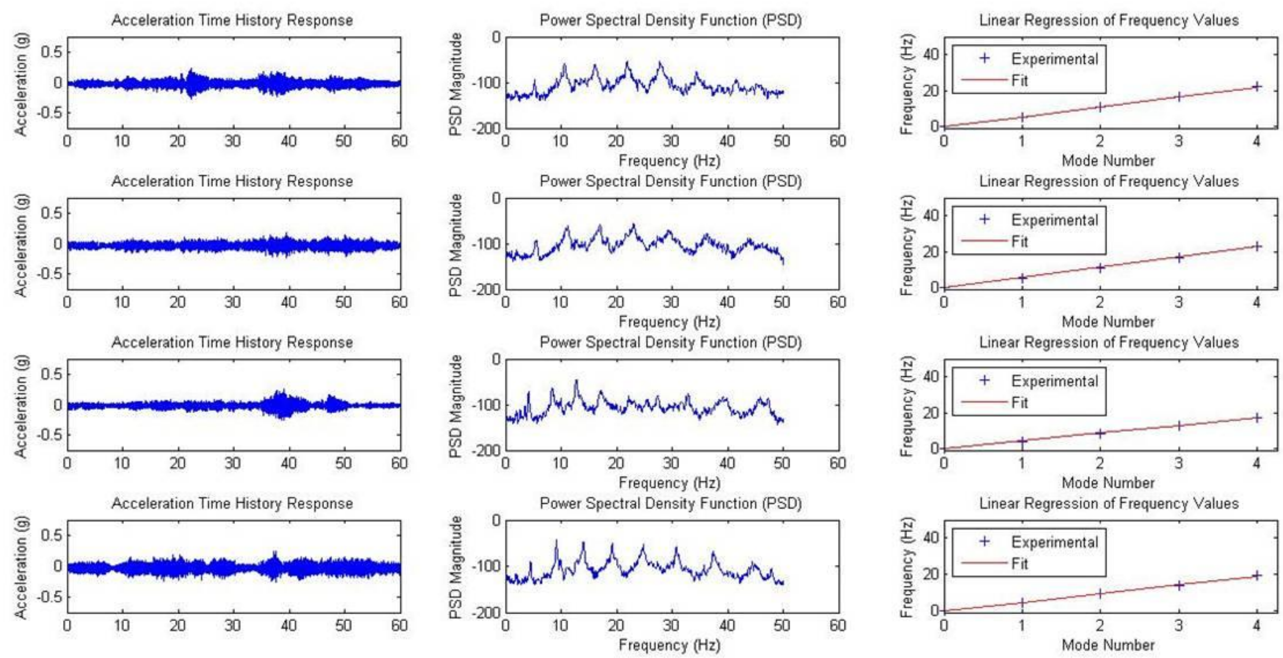
L3N	w1 (Hz)	w2 (Hz)	w3 (Hz)	w4 (Hz)	wfit (Hz)	Norm of R	T (k)
1	9.00	18.00	28.22	40.15	9.95	1.97	45.07
2	10.81	21.76	33.60	46.80	11.64	1.57	61.65
3	11.84	23.62			11.81	0.02	63.48
4	11.59	23.43	35.75		11.91	0.37	64.53

Cable Set L4N



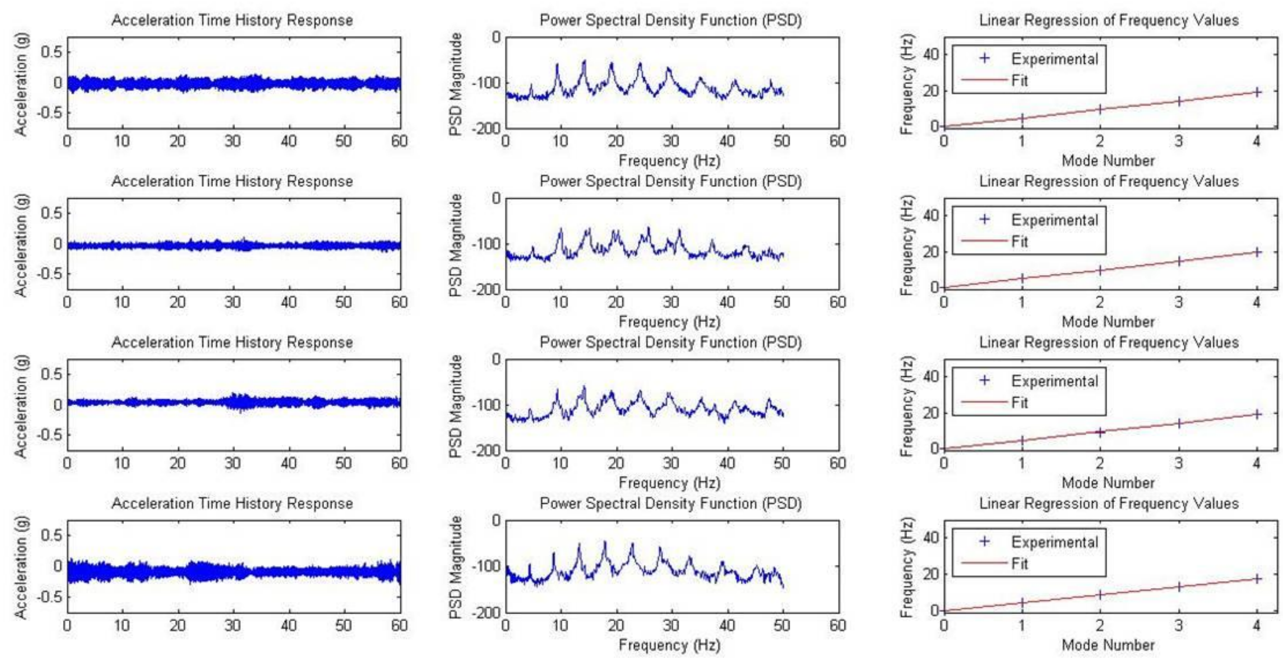
L4N	w1 (Hz)	w2 (Hz)	w3 (Hz)	w4 (Hz)	wfit (Hz)	Norm of R	T (k)
1	8.02	16.19	24.55	33.99	8.45	0.87	73.12
2	6.02	11.88	18.19	25.04	6.23	0.61	39.68
3	7.63	15.41	23.43	32.03	7.99	0.61	65.30
4	7.53	15.21	23.48	32.03	8.00	0.71	65.54

Cable Set L5N



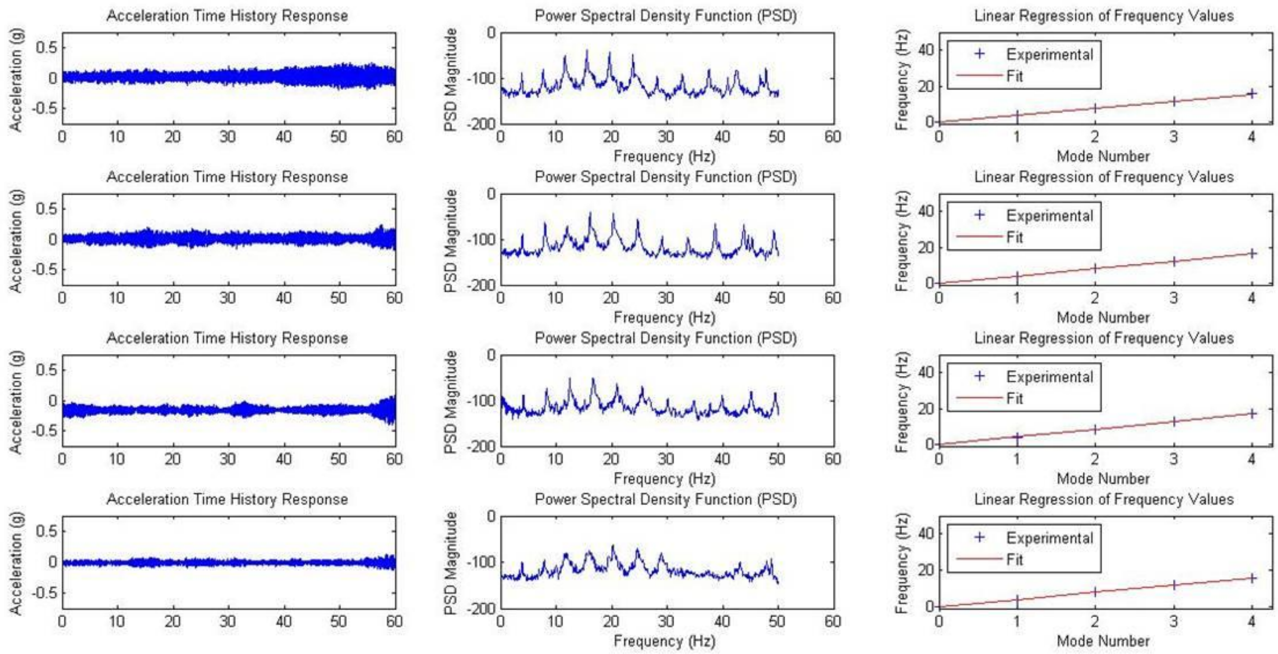
L5N	w1 (Hz)	w2 (Hz)	w3 (Hz)	w4 (Hz)	wfit (Hz)	Norm of R	T (k)
1	5.28	10.66	16.29	22.11	5.52	0.36	51.30
2	5.33	10.96	16.77	22.84	5.71	0.45	54.91
3	4.06	8.56	12.91	17.36	4.36	0.22	31.95
4	4.40	9.34	13.79	19.17	4.77	0.50	38.34

Cable Set L6N



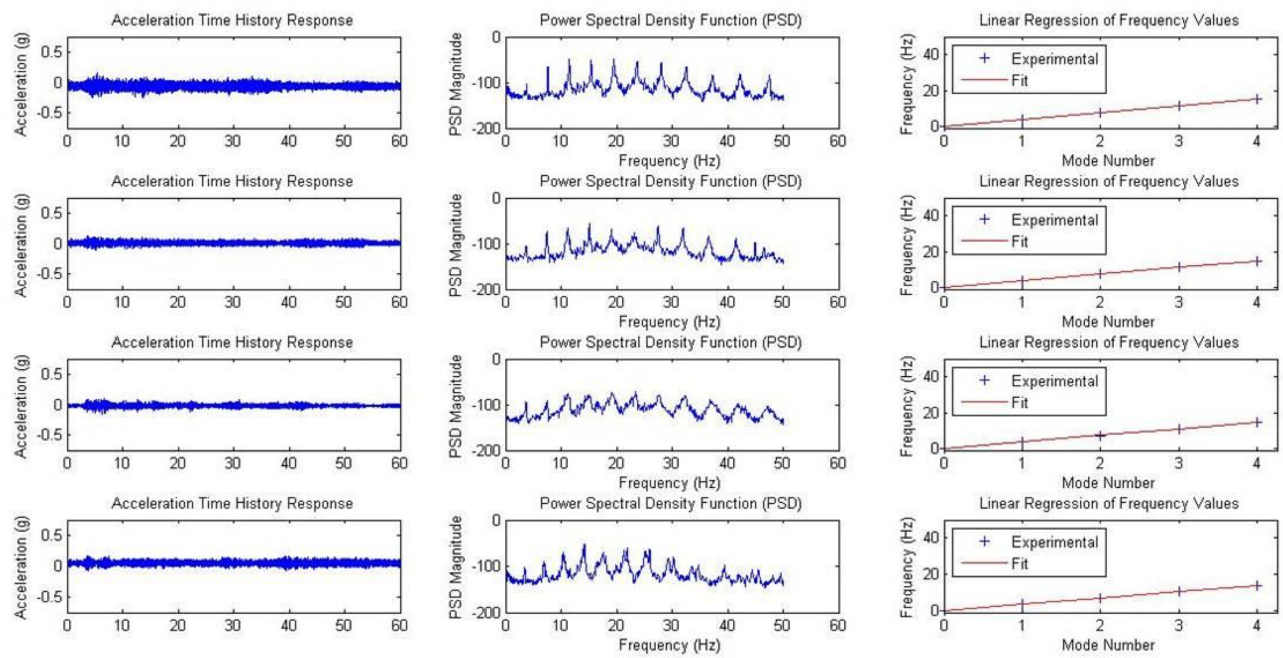
L6N	w1 (Hz)	w2 (Hz)	w3 (Hz)	w4 (Hz)	wfit (Hz)	Norm of R	T (k)
1	4.70	9.44	14.13	19.22	4.79	0.23	53.72
2	4.74	9.83	14.67	19.86	4.96	0.22	57.74
3	4.45	9.19	13.99	19.07	4.77	0.36	53.28
4	4.25	8.71	13.25	17.80	4.46	0.19	46.61

Cable Set L7N



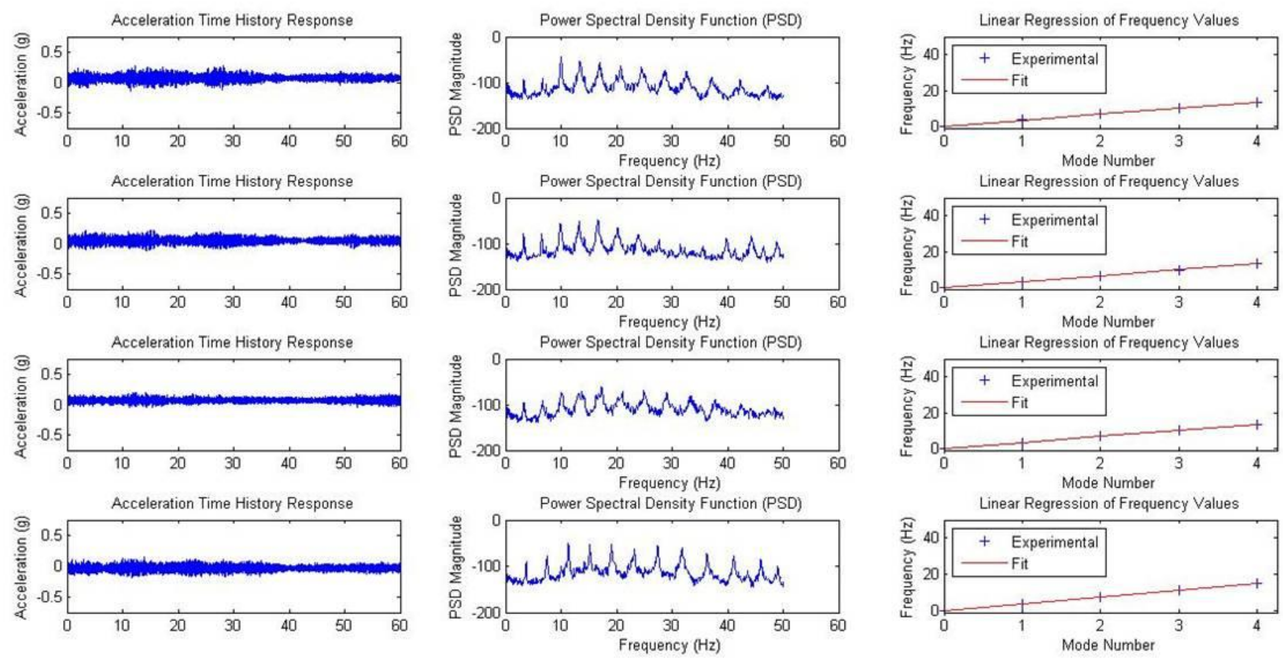
L7N	w1 (Hz)	w2 (Hz)	w3 (Hz)	w4 (Hz)	wfit (Hz)	Norm of R	T (k)
1	3.91	7.78	11.59	15.60	3.89	0.09	44.33
2	4.06	8.22	11.93	16.38	4.06	0.30	48.43
3	4.01	8.51	12.62	16.92	4.25	0.21	52.84
4	3.81	8.02	11.69	15.89	3.97	0.25	46.13

Cable Set L8N



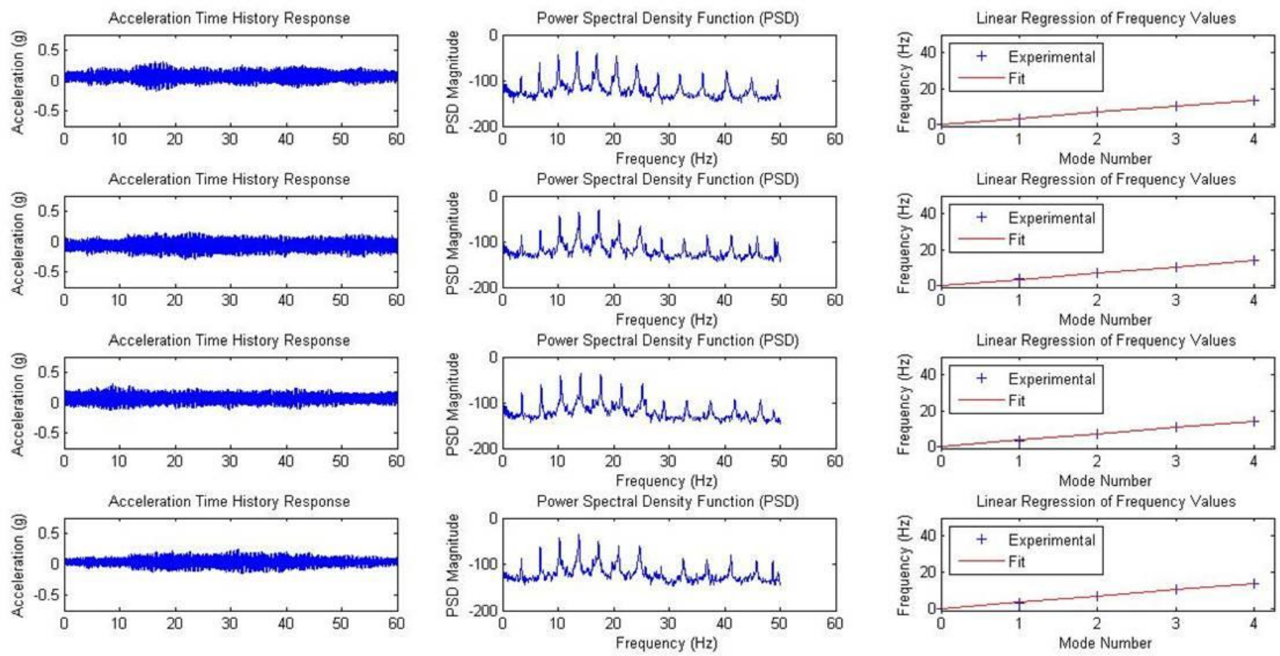
L8N	w1 (Hz)	w2 (Hz)	w3 (Hz)	w4 (Hz)	wfit (Hz)	Norm of R	T (k)
1	3.67	7.73	11.44	15.50	3.88	0.21	51.04
2	3.67	7.34	11.15	14.87	3.72	0.09	47.00
3	3.57	7.19	11.10	14.82	3.72	0.20	46.88
4	3.42	7.09	10.51	13.94	3.50	0.13	41.49

<u>Cable Set L9N</u>



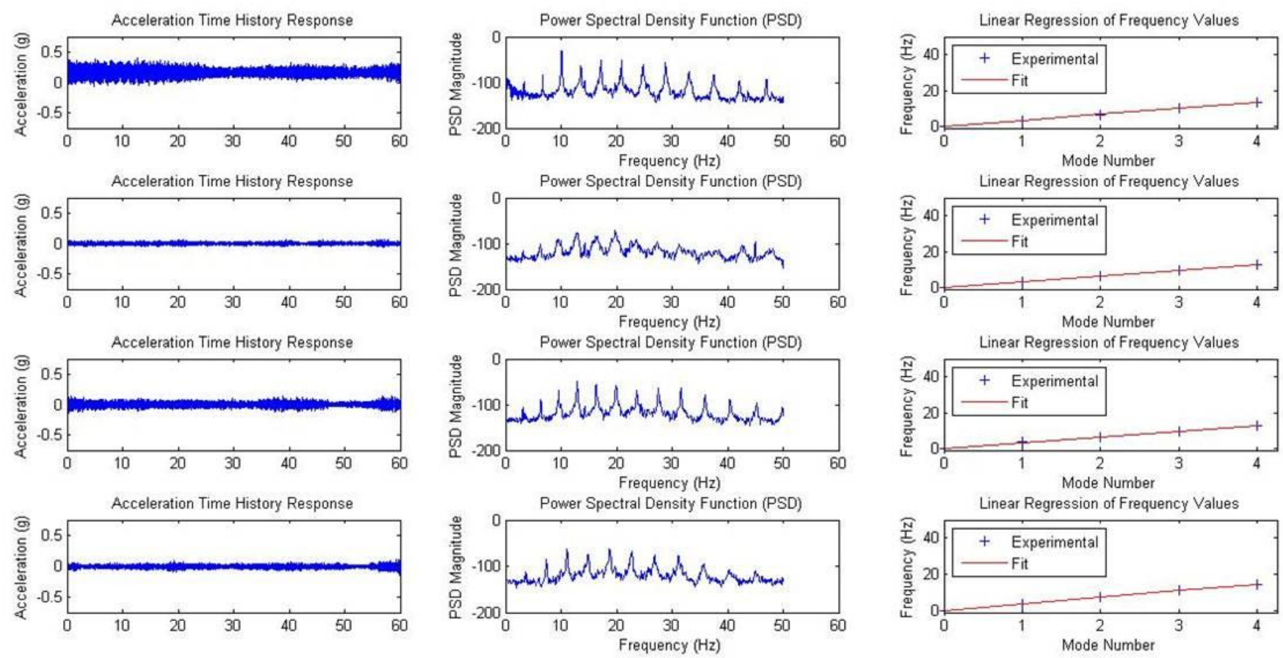
L9N	w1 (Hz)	w2 (Hz)	w3 (Hz)	w4 (Hz)	wfit (Hz)	Norm of R	T (k)
1	3.47	6.80	9.93	13.35	3.32	0.17	40.53
2	3.37	6.60	9.83	13.20	3.29	0.09	39.81
3	3.42	6.80	10.03	13.45	3.35	0.10	41.37
4	3.77	7.58	11.15	15.26	3.79	0.23	52.95

Cable Set L10N



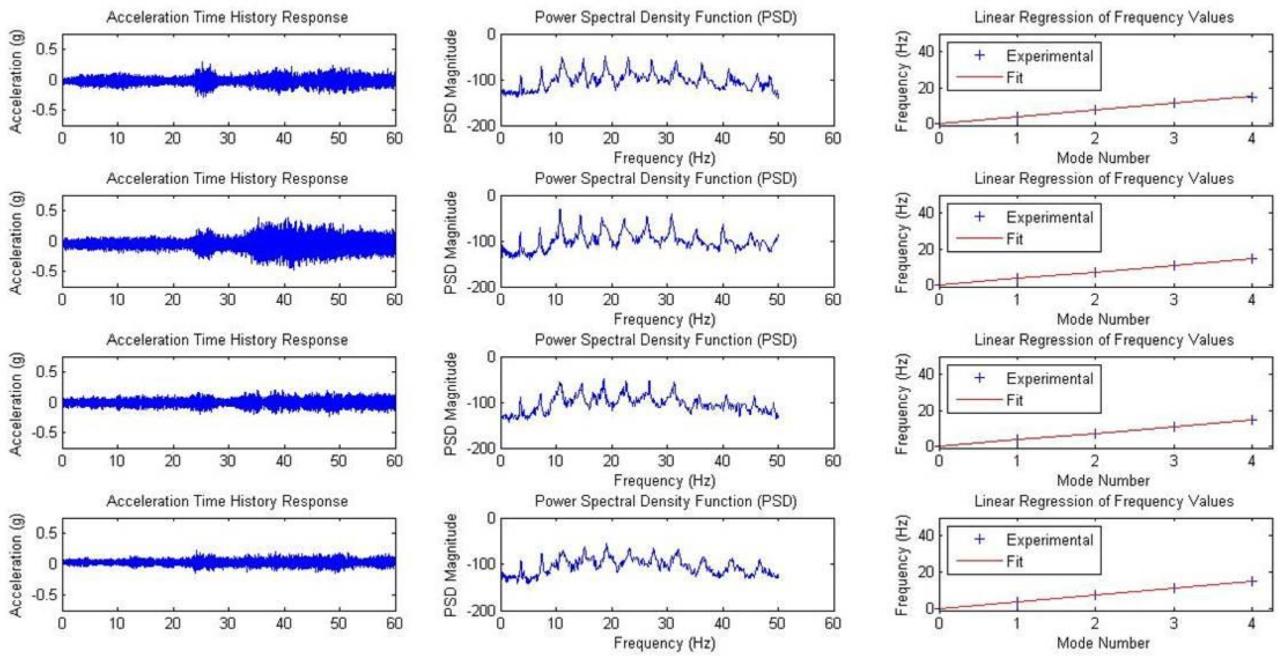
L10N	w1 (Hz)	w2 (Hz)	w3 (Hz)	w4 (Hz)	wfit (Hz)	Norm of R	T (k)
1	3.23	6.65	10.22	13.35	3.37	0.21	42.99
2	3.47	6.80	10.47	13.74	3.45	0.17	45.01
3	3.33	7.09	10.51	13.99	3.52	0.19	46.82
4	3.37	6.94	10.47	13.69	3.45	0.18	45.01

Cable Set L11N



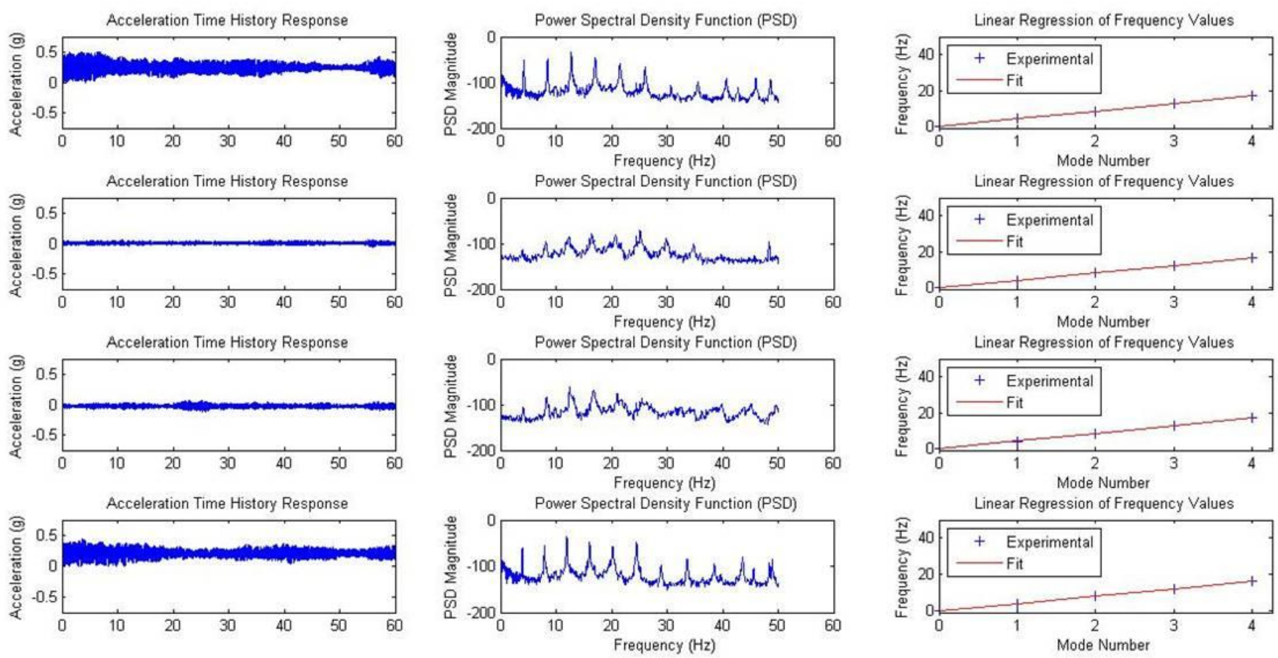
L11N	w1 (Hz)	w2 (Hz)	w3 (Hz)	w4 (Hz)	wfit (Hz)	Norm of R	T (k)
1	3.42	6.60	10.17	13.55	3.38	0.17	42.22
2	3.33	6.16	9.63	12.81	3.19	0.27	37.59
3	3.47	6.31	9.63	12.81	3.18	0.26	37.25
4	3.42	7.24	11.20	14.67	3.71	0.29	50.79

Cable Set L12N



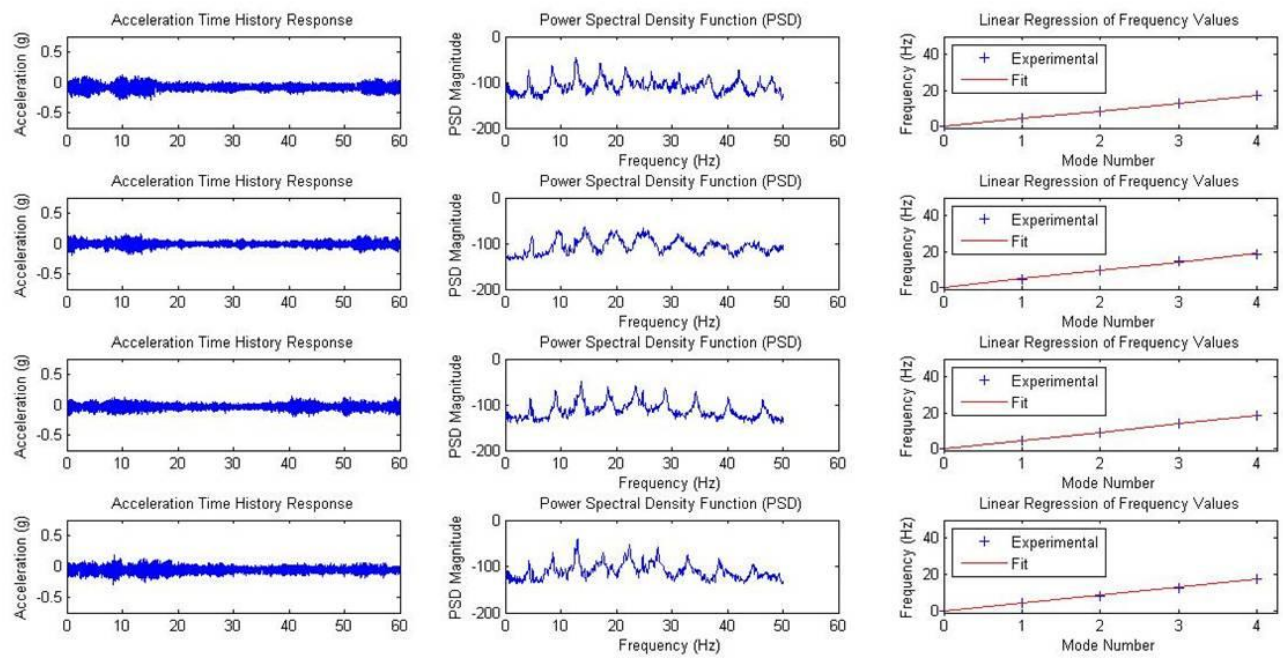
L12N	w1 (Hz)	w2 (Hz)	w3 (Hz)	w4 (Hz)	wfit (Hz)	Norm of R	T (k)
1	3.81	7.48	11.30	14.92	3.73	0.10	47.25
2	3.62	7.19	10.86	14.48	3.62	0.04	44.44
3	3.81	7.19	10.81	14.43	3.58	0.18	43.61
4	3.86	7.63	11.25	15.06	3.75	0.12	47.75

Cable Set L13N



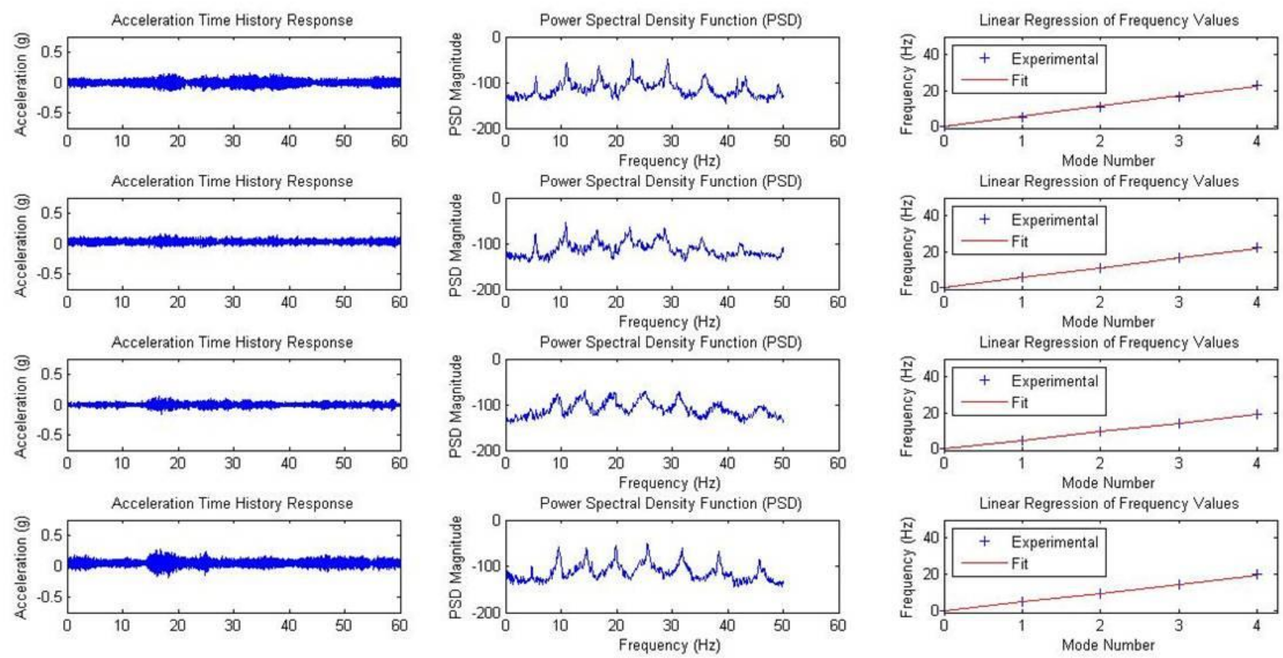
L13N	w1 (Hz)	w2 (Hz)	w3 (Hz)	w4 (Hz)	wfit (Hz)	Norm of R	T (k)
1	4.11	8.56	12.91	17.12	4.30	0.16	54.31
2	3.91	7.97	12.32	16.53	4.15	0.26	50.43
3	4.06	8.36	12.81	16.87	4.25	0.21	52.96
4	3.91	8.07	12.08	16.09	4.03	0.10	47.73

Cable Set L14N



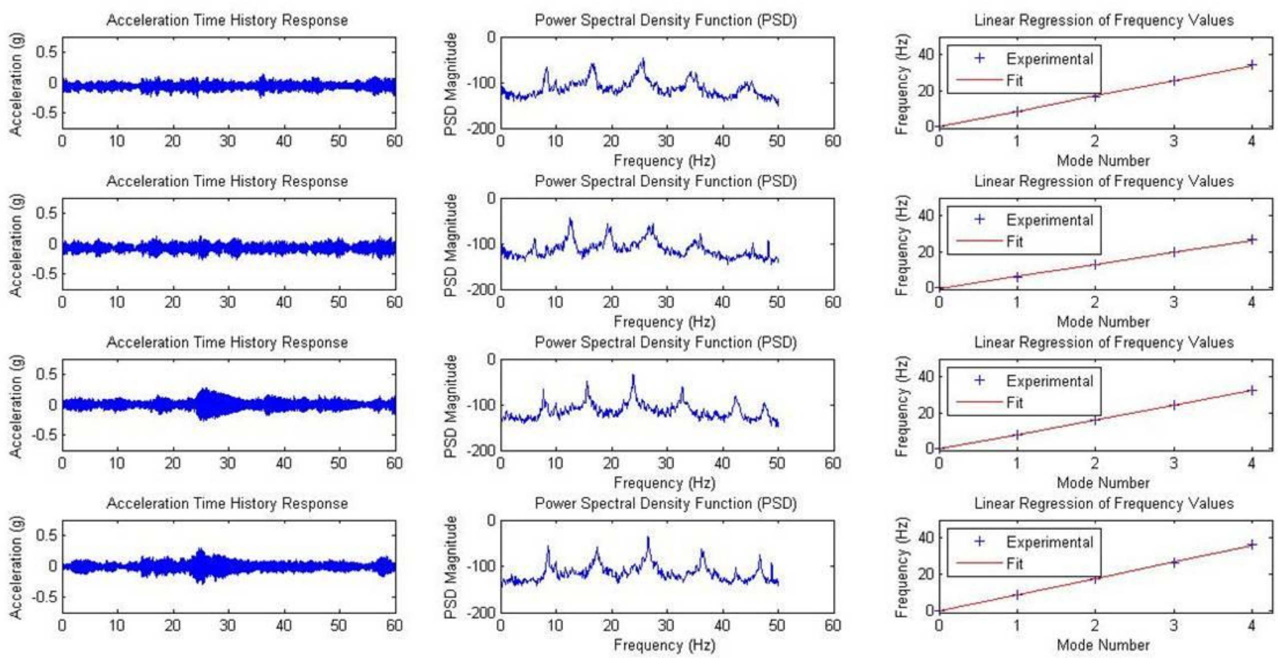
L14N	w1 (Hz)	w2 (Hz)	w3 (Hz)	w4 (Hz)	wfit (Hz)	Norm of R	T (k)
1	4.25	8.41	12.72	17.31	4.31	0.25	43.50
2	4.65	9.59	14.33	18.68	4.70	0.30	51.87
3	4.50	9.05	13.69	18.63	4.65	0.27	50.58
4	4.16	8.41	12.81	17.56	4.38	0.36	44.89

Cable Set L15N



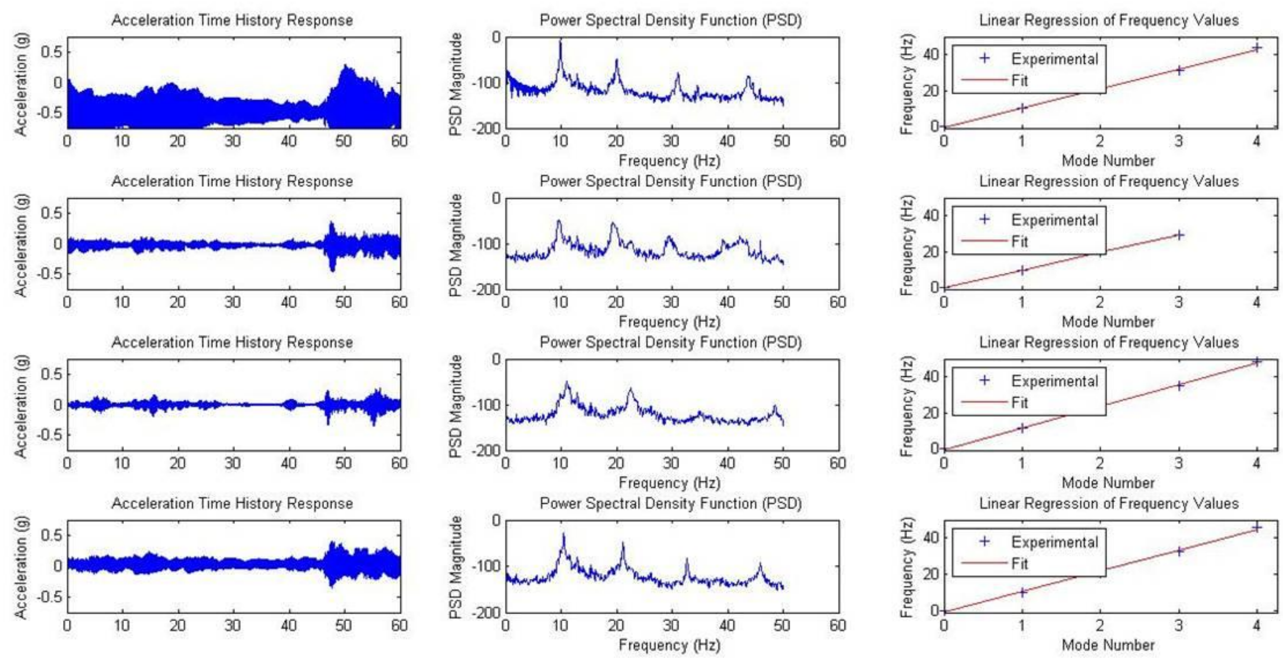
L15N	w1 (Hz)	w2 (Hz)	w3 (Hz)	w4 (Hz)	wfit (Hz)	Norm of R	T (k)
1	5.33	11.05	16.82	22.69	5.69	0.32	54.44
2	5.43	10.71	16.29	22.15	5.52	0.35	51.21
3	4.45	9.39	13.99	19.32	4.82	0.45	39.05
4	4.70	9.44	14.43	19.86	4.94	0.47	41.14

Cable Set L16N



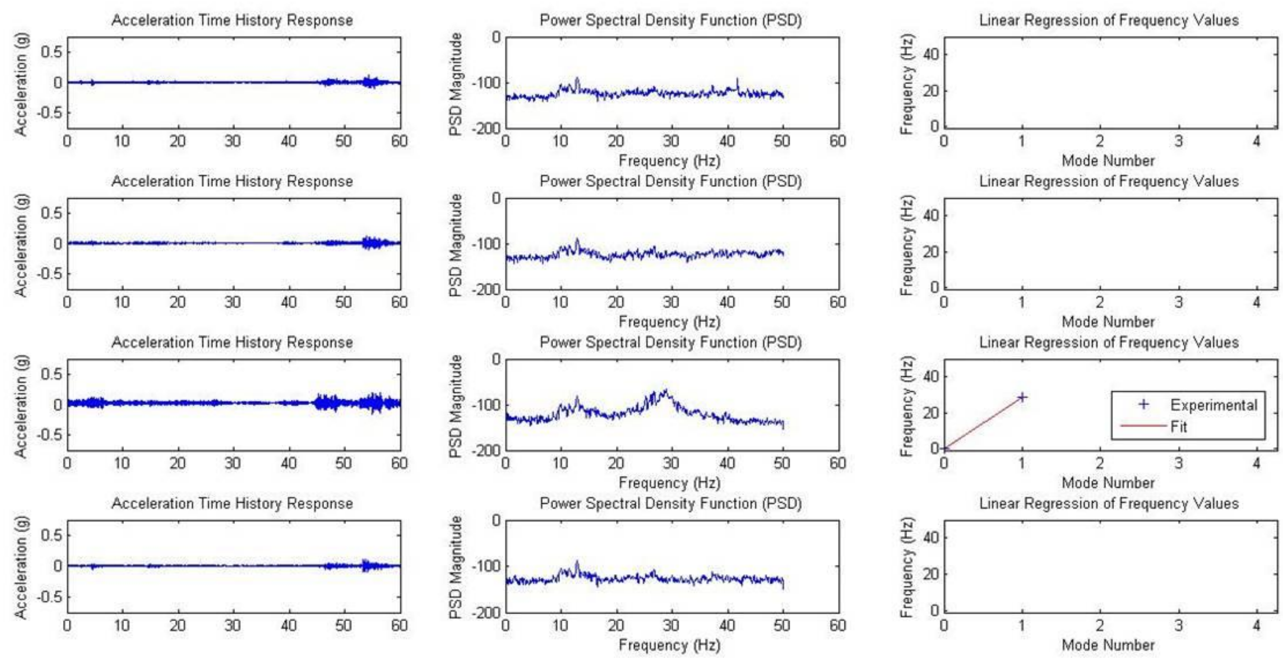
L16N	w1 (Hz)	w2 (Hz)	w3 (Hz)	w4 (Hz)	wfit (Hz)	Norm of R	T (k)
1	8.36	16.63	25.43	34.19	8.54	0.38	74.74
2	5.97	12.52	19.42	26.90	6.72	0.90	46.30
3	7.92	15.60	24.01	32.62	8.13	0.61	67.72
4	8.66	17.51	26.56	36.29	9.05	0.65	83.81

Cable Set L17N



L17N	w1 (Hz)	w2 (Hz)	w3 (Hz)	w4 (Hz)	wfit (Hz)	Norm of R	T (k)
1	9.98	20.10	31.10	43.72	10.86	1.71	53.64
2	9.59	19.51	29.44		9.83	0.19	43.93
3	11.15	22.50	34.87	48.47	12.07	1.62	66.24
4	10.27	21.03	32.62	45.97	11.43	1.91	59.44

Cable Set L18N

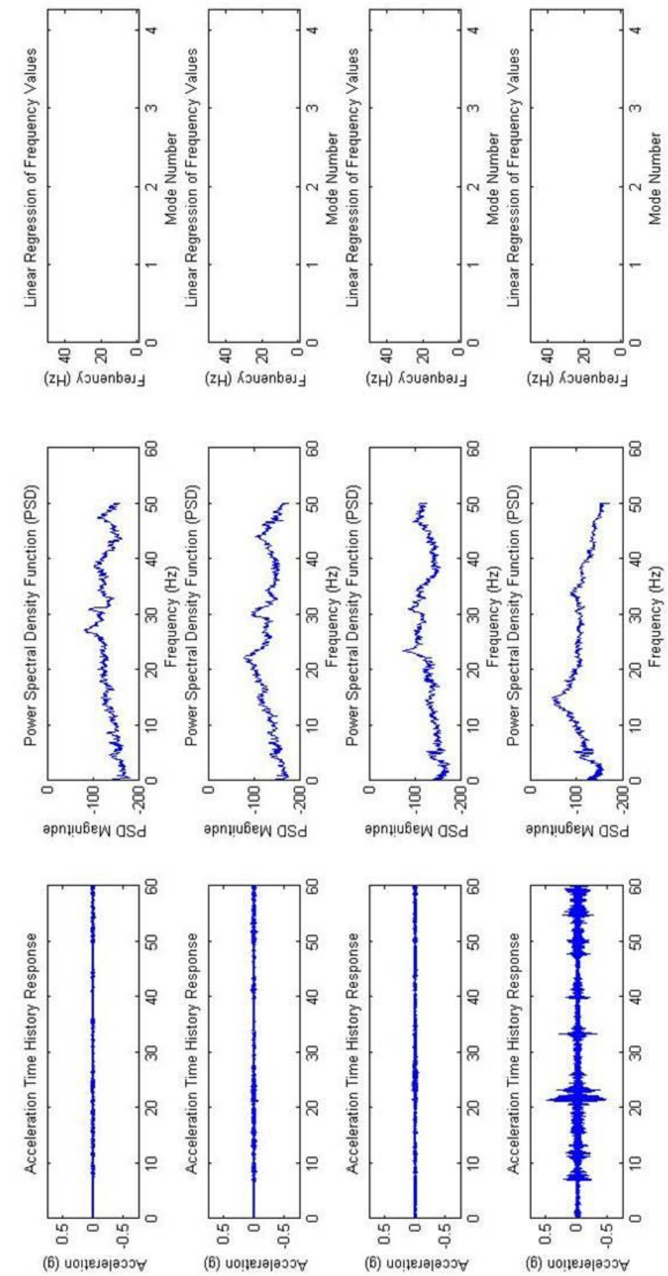


L18N	w1 (Hz)	w2 (Hz)	w3 (Hz)	w4 (Hz)	wfit (Hz)	Norm of R	T (k)
1							
2							
3							
4							

Appendix D – Construction Phase – Cable Tension Graphs and Tables

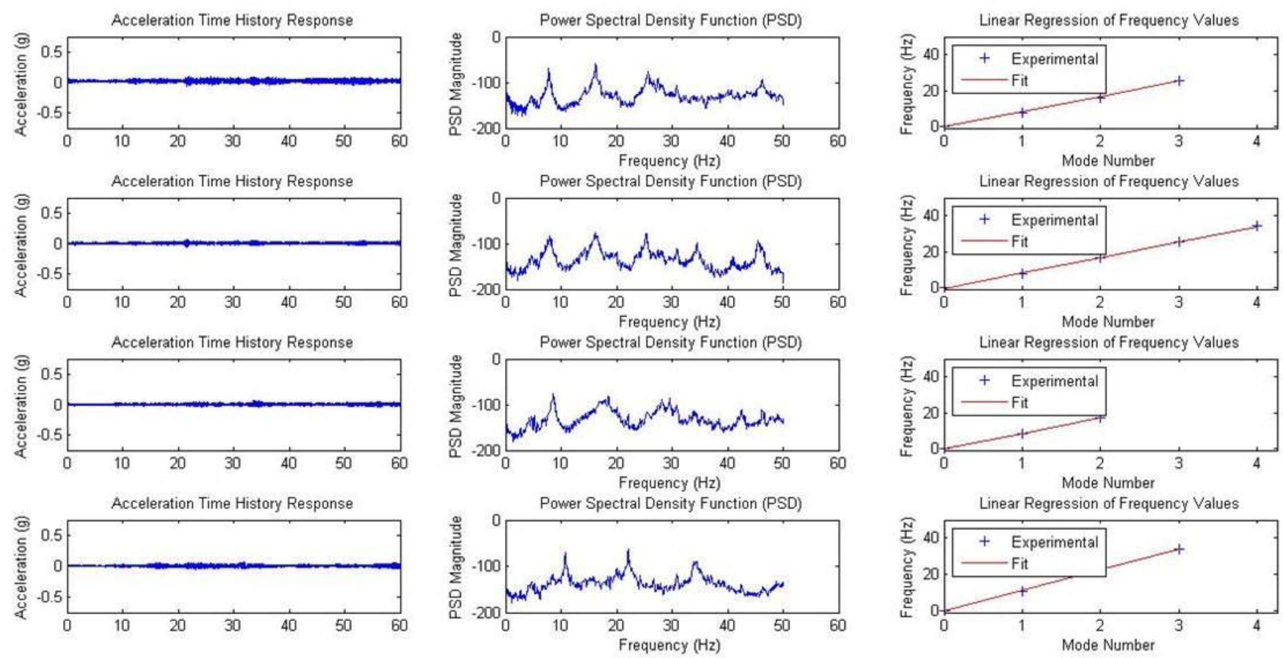
SOUTH SPAN

Cable Set L2



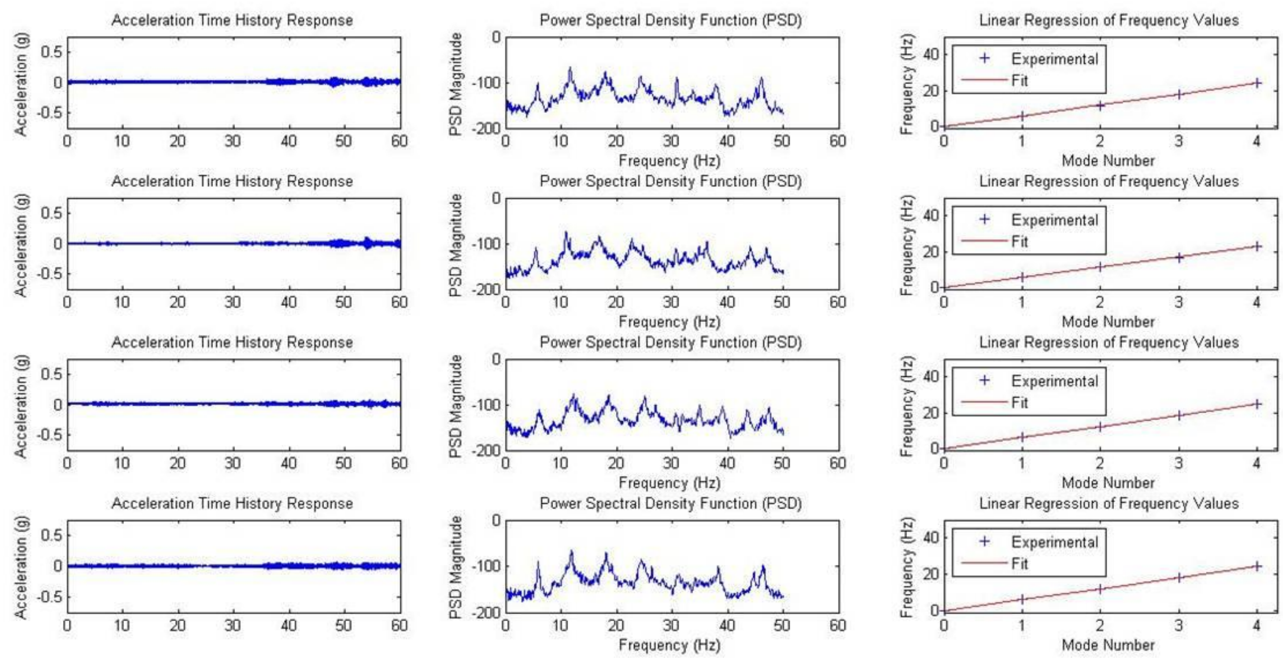
L2	w1 (Hz)	w2 (Hz)	w3 (Hz)	w4 (Hz)	wfit (Hz)	Norm of R	T (k)
1							
2							
3							
4							

<u>Cable Set L3</u>



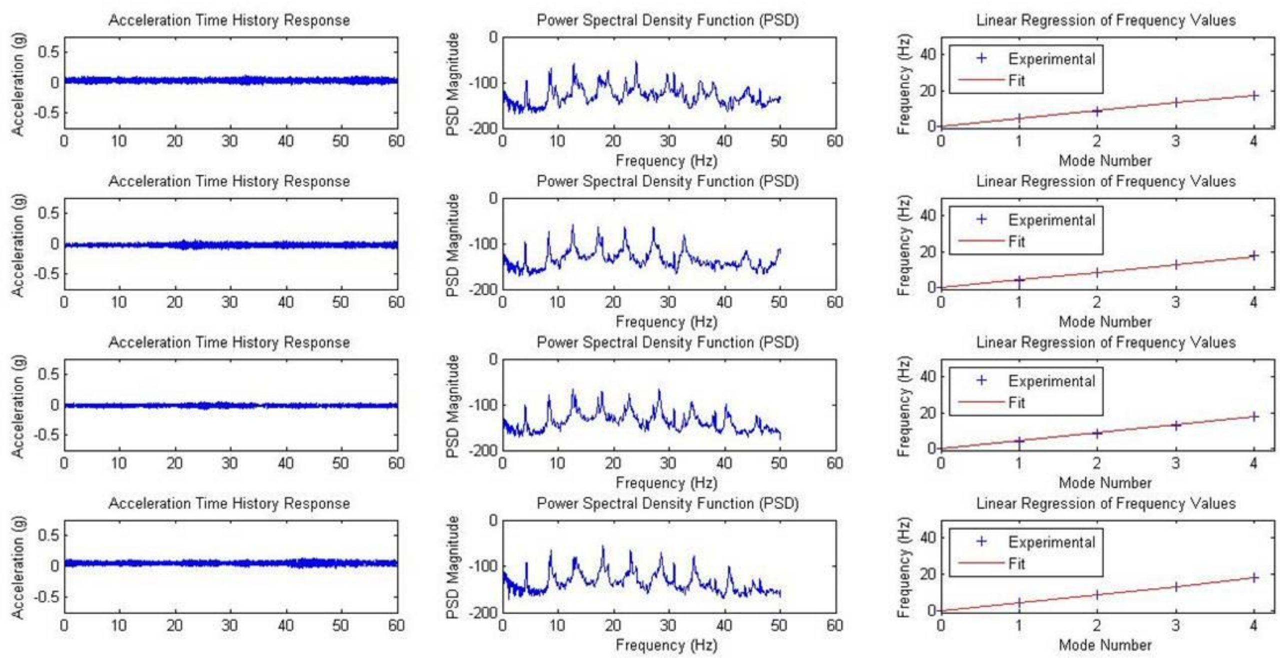
L3	w1 (Hz)	w2 (Hz)	w3 (Hz)	w4 (Hz)	wfit (Hz)	Norm of R	T (k)
1	7.87	16.14	25.72		8.54	0.88	33.22
2	7.87	16.33	25.38	34.38	8.63	0.79	33.87
3	8.46	16.87			8.44	0.02	32.39
4	10.71	22.15	34.14		11.39	0.64	58.99

Cable Set L4



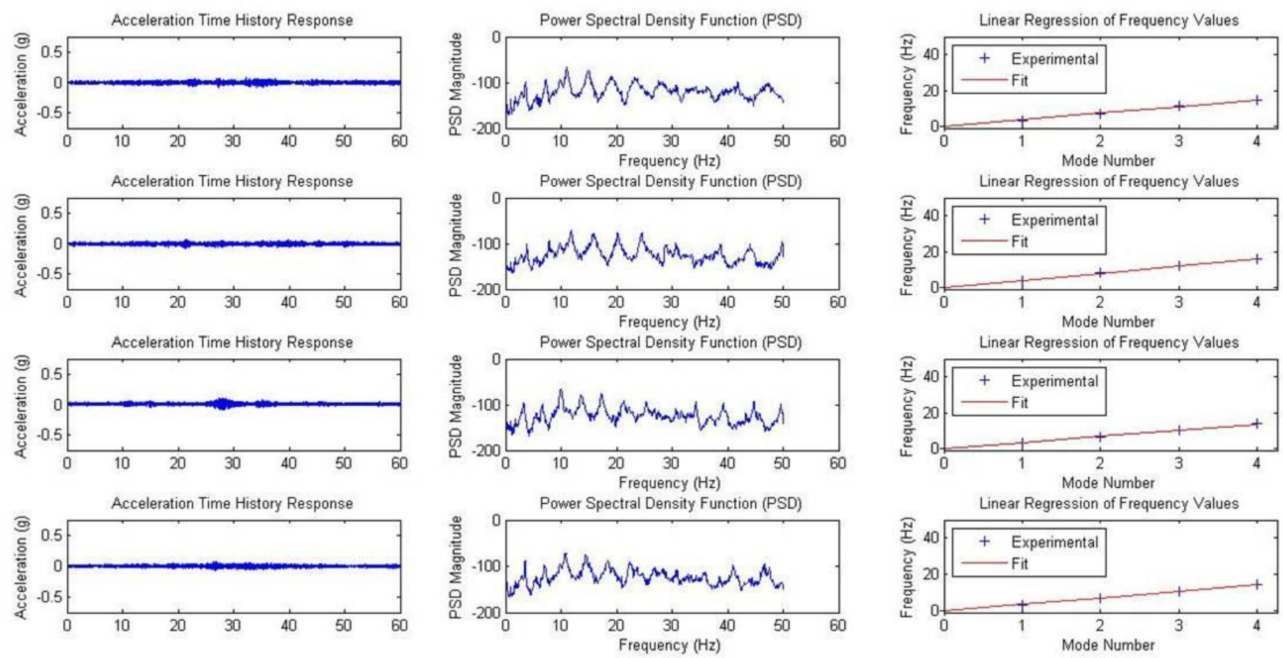
L4	w1 (Hz)	w2 (Hz)	w3 (Hz)	w4 (Hz)	wfit (Hz)	Norm of R	T (k)
1	5.72	11.74	17.85	24.40	6.09	0.48	38.02
2	5.48	11.15	16.82	22.74	5.68	0.24	33.07
3	6.11	12.08	18.58	25.04	6.26	0.36	40.06
4	6.02	11.74	18.19	24.55	6.13	0.44	38.45

Cable Set L5



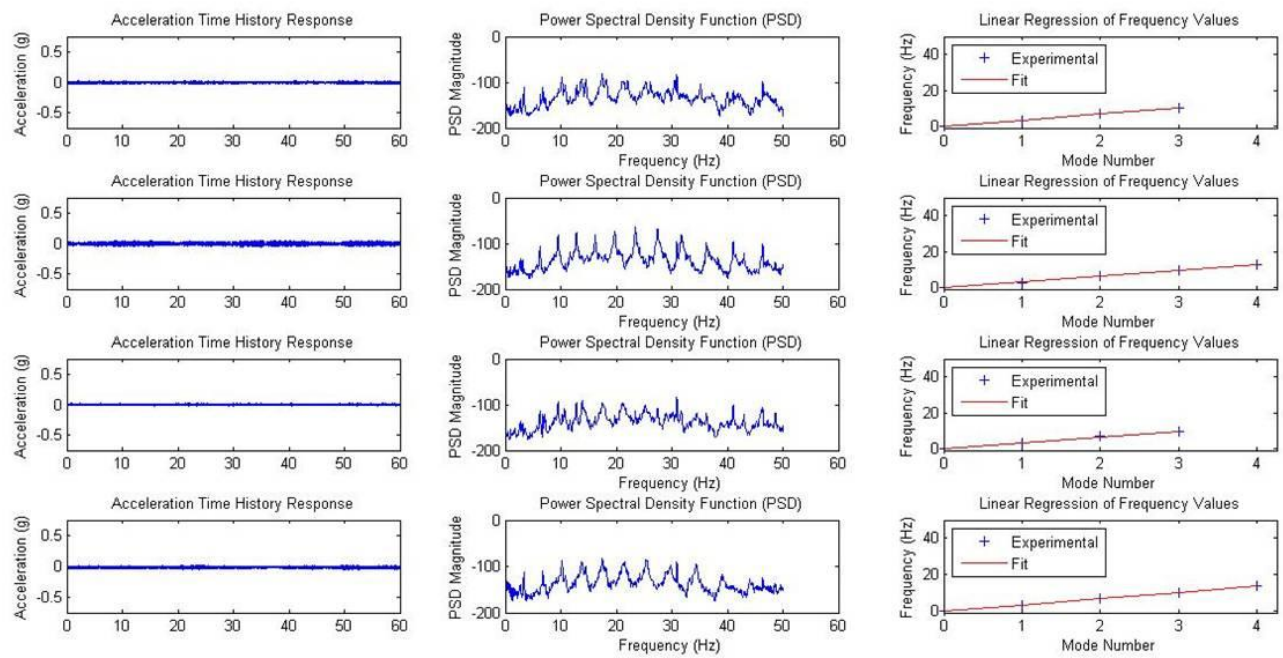
L5	w1 (Hz)	w2 (Hz)	w3 (Hz)	w4 (Hz)	wfit (Hz)	Norm of R	T (k)
1	4.35	8.56	13.20	17.41	4.37	0.20	32.10
2	3.96	8.27	12.62	17.51	4.37	0.52	32.10
3	4.06	8.56	12.86	17.85	4.45	0.49	33.33
4	4.16	8.71	13.35	18.05	4.53	0.33	34.51

Cable Set L6



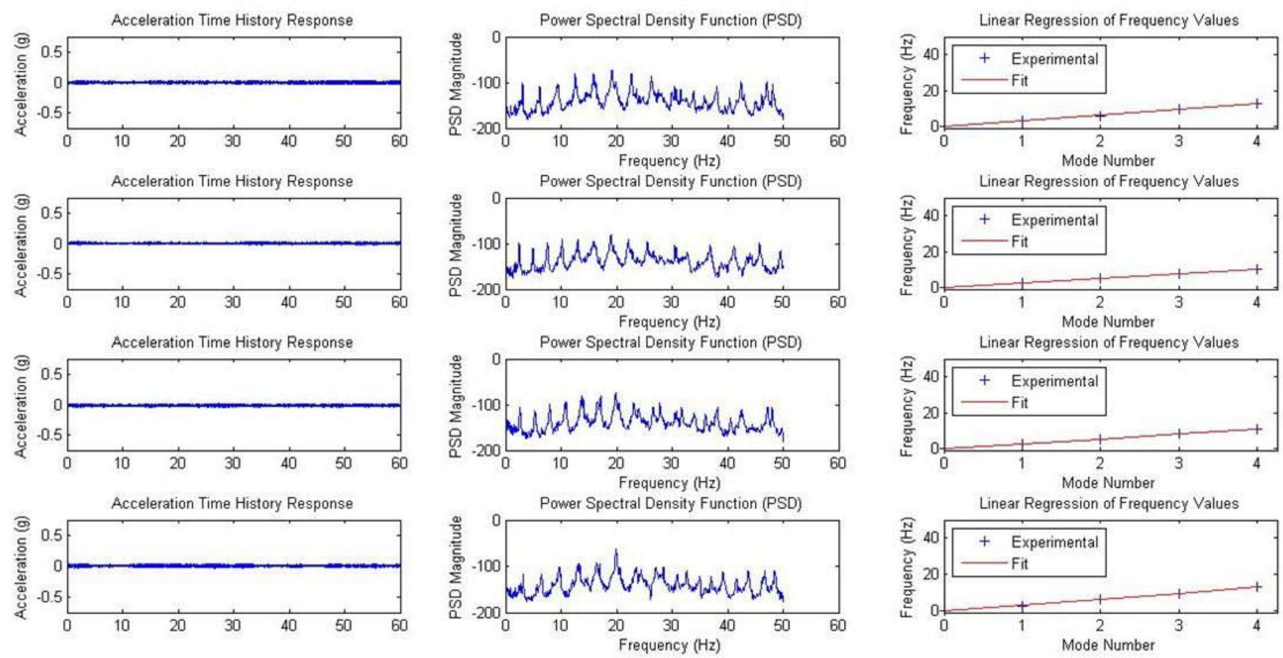
L6	w1 (Hz)	w2 (Hz)	w3 (Hz)	w4 (Hz)	wfit (Hz)	Norm of R	T (k)
1	3.42	7.29	11.20	14.82	3.74	0.26	32.80
2	3.77	8.07	11.79	15.99	4.00	0.27	37.50
3	3.08	6.55	10.03	13.79	3.45	0.38	27.93
4	3.28	7.14	10.86	14.48	3.65	0.28	31.27

Cable Set L7



L7	w1 (Hz)	w2 (Hz)	w3 (Hz)	w4 (Hz)	wfit (Hz)	Norm of R	T (k)
1	3.03	6.75	10.27		3.45	0.31	34.96
2	2.74	6.16	9.44	12.67	3.20	0.34	30.09
3	2.89	6.99	9.24		3.18	0.76	29.72
4	2.89	6.80	10.22	13.94	3.52	0.48	36.36

Cable Set L8



L8	w1 (Hz)	w2 (Hz)	w3 (Hz)	w4 (Hz)	wfit (Hz)	Norm of R	T (k)
1	2.84	5.87	9.29	12.72	3.19	0.43	34.50
2	2.40	5.09	7.48	10.12	2.53	0.15	21.78
3	2.45	5.18	8.02	10.86	2.73	0.25	25.27
4	2.74	6.26	9.59	13.20	3.33	0.48	37.53

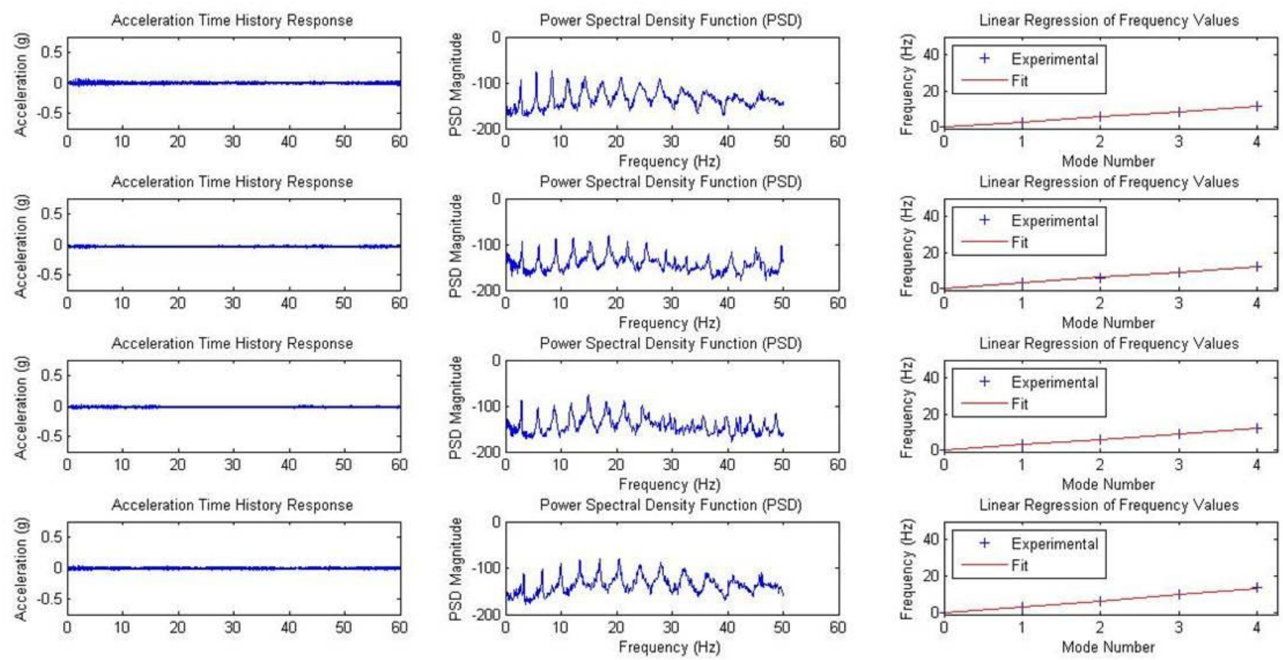
Cable Set L9

L9	w1 (Hz)	w2 (Hz)	w3 (Hz)	w4 (Hz)	wfit (Hz)	Norm of R	T (k)
1							
2							
3							
4							

Cable Set L10

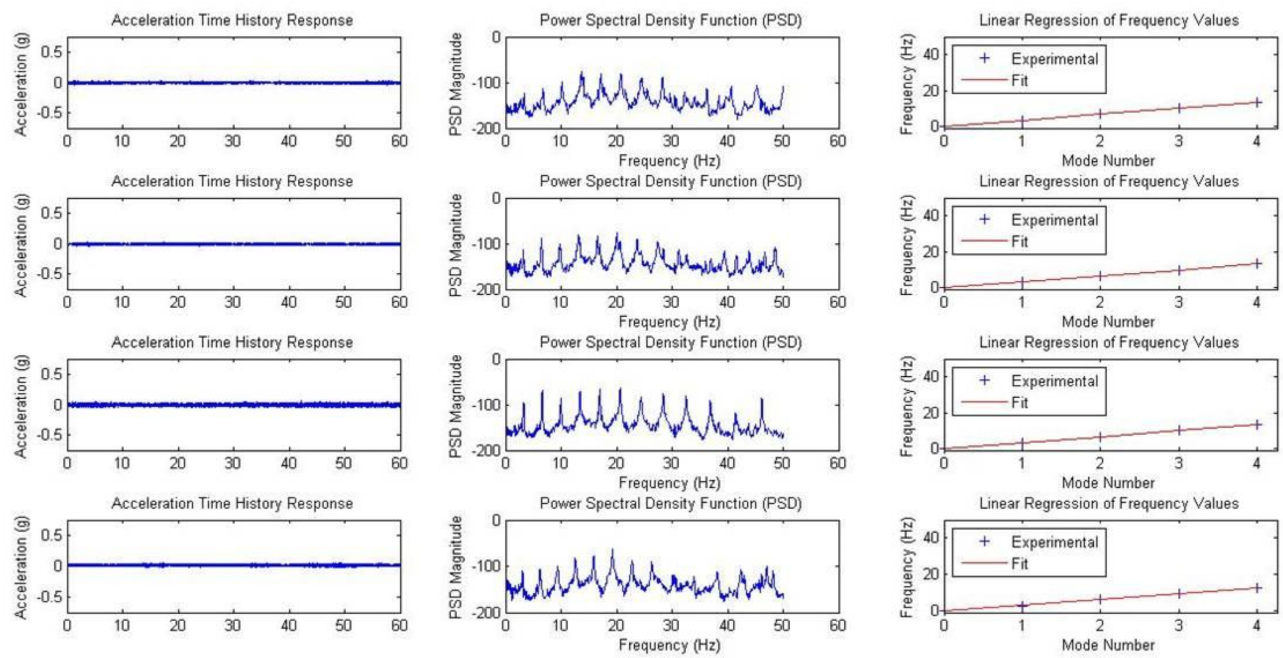
L10	w1 (Hz)	w2 (Hz)	w3 (Hz)	w4 (Hz)	wfit (Hz)	Norm of R	T (k)
1							
2							
3							
4							

Cable Set L11



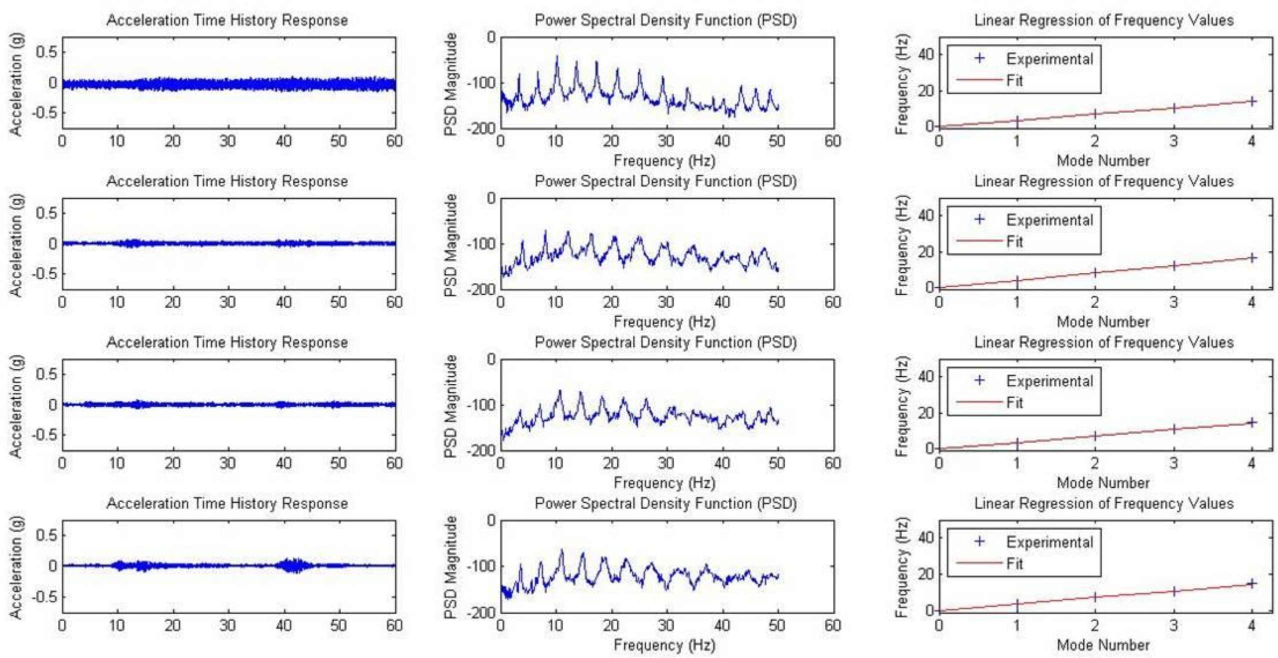
L11	w1 (Hz)	w2 (Hz)	w3 (Hz)	w4 (Hz)	wfit (Hz)	Norm of R	T (k)
1	2.74	5.58	8.41	11.30	2.83	0.08	29.45
2	2.93	5.97	8.90	12.28	3.05	0.25	34.33
3	2.84	5.82	8.71	11.93	2.97	0.21	32.59
4	2.84	6.46	9.83	13.50	3.40	0.45	42.59

Cable Set L12



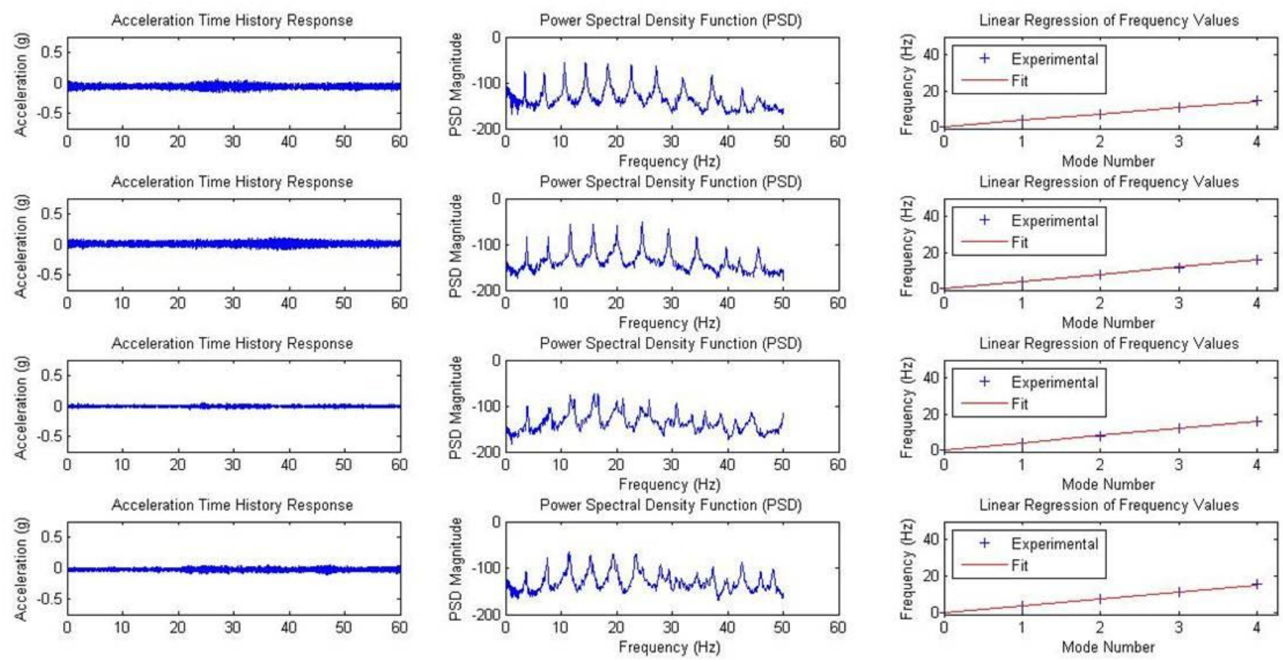
L12	w1 (Hz)	w2 (Hz)	w3 (Hz)	w4 (Hz)	wfit (Hz)	Norm of R	T (k)
1	2.89	6.70	10.27	13.64	3.47	0.43	40.80
2	3.03	6.26	9.59	13.25	3.31	0.37	37.09
3	2.93	6.46	9.98	13.40	3.38	0.34	38.86
4	2.74	6.26	9.39	12.72	3.21	0.35	34.93

Cable Set L13



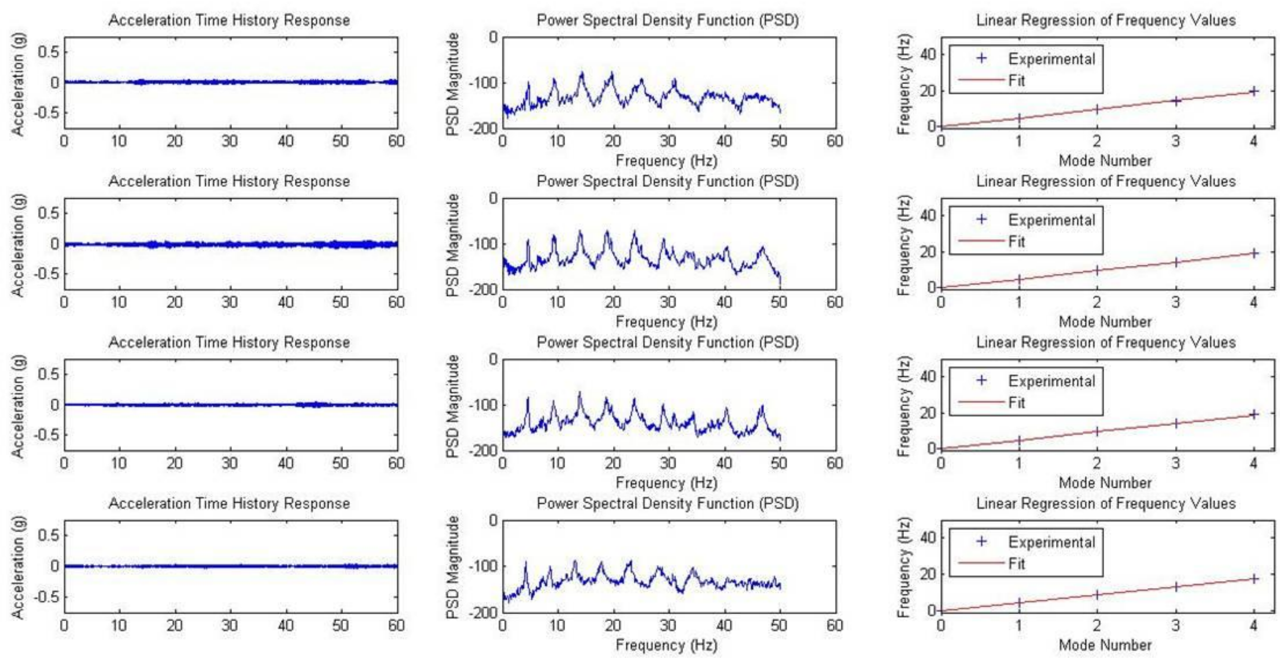
L13	w1 (Hz)	w2 (Hz)	w3 (Hz)	w4 (Hz)	wfit (Hz)	Norm of R	T (k)
1	3.33	6.85	10.12	13.84	3.45	0.21	34.86
2	3.81	8.07	12.13	16.38	4.11	0.23	49.49
3	3.23	6.85	10.51	14.38	3.60	0.36	38.09
4	3.47	7.19	10.81	14.82	3.70	0.28	40.08

Cable Set L14



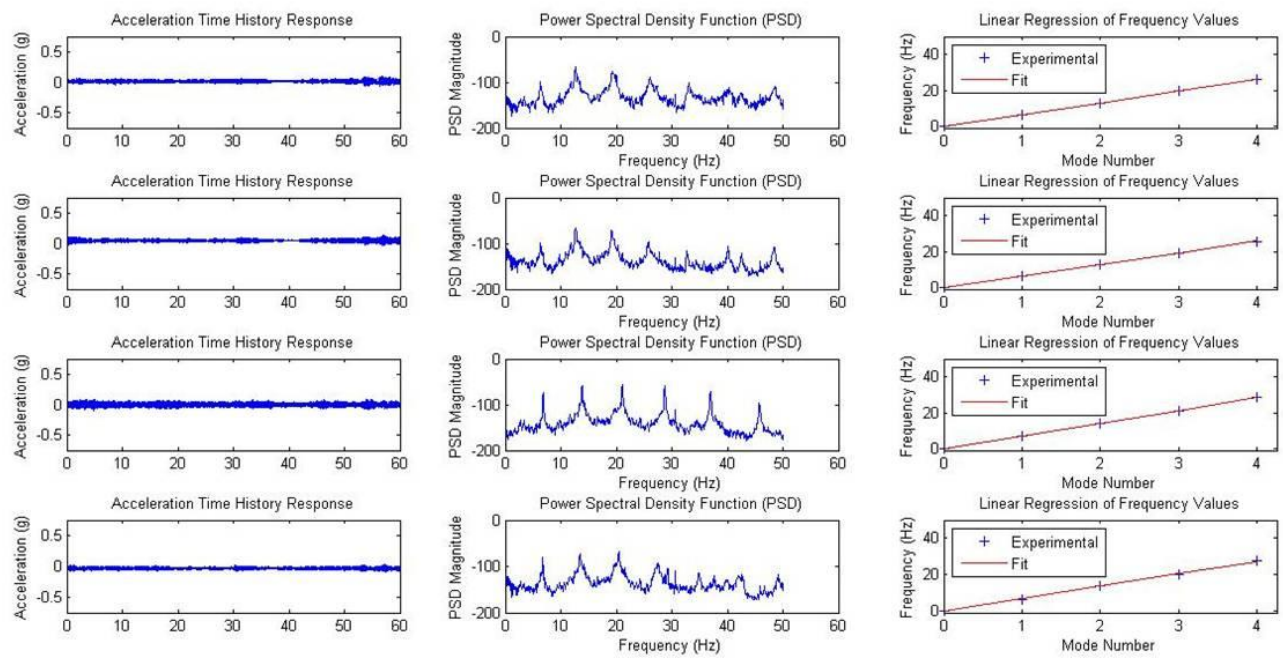
L14	w1 (Hz)	w2 (Hz)	w3 (Hz)	w4 (Hz)	wfit (Hz)	Norm of R	T (k)
1	3.52	6.75	10.56	14.38	3.58	0.37	30.03
2	3.72	7.78	11.69	15.89	3.98	0.25	37.04
3	3.91	7.92	12.03	16.19	4.05	0.16	38.42
4	3.67	7.38	11.40	15.41	3.85	0.27	34.80

Cable Set L15



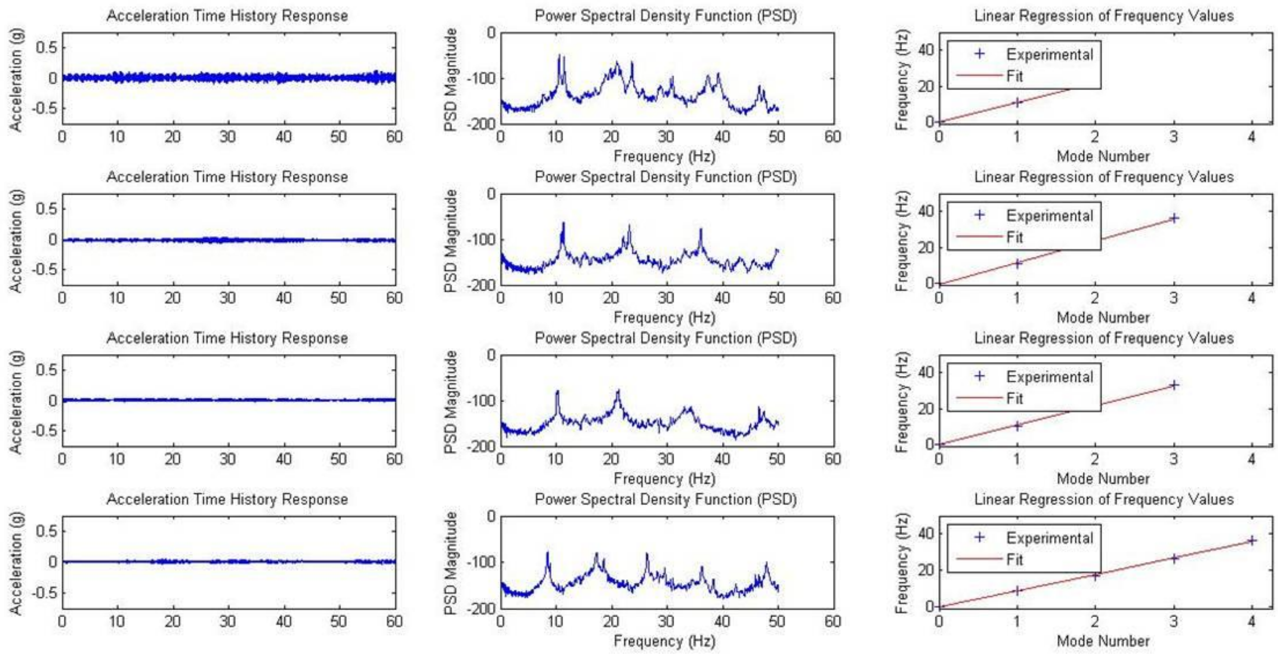
L15	w1 (Hz)	w2 (Hz)	w3 (Hz)	w4 (Hz)	wfit (Hz)	Norm of R	T (k)
1	4.55	9.24	14.18	19.51	4.87	0.49	39.85
2	4.40	9.24	13.99	18.98	4.75	0.31	38.03
3	4.45	9.39	13.89	18.88	4.72	0.28	37.48
4	4.11	8.61	13.06	17.80	4.46	0.34	33.40

Cable Set L16



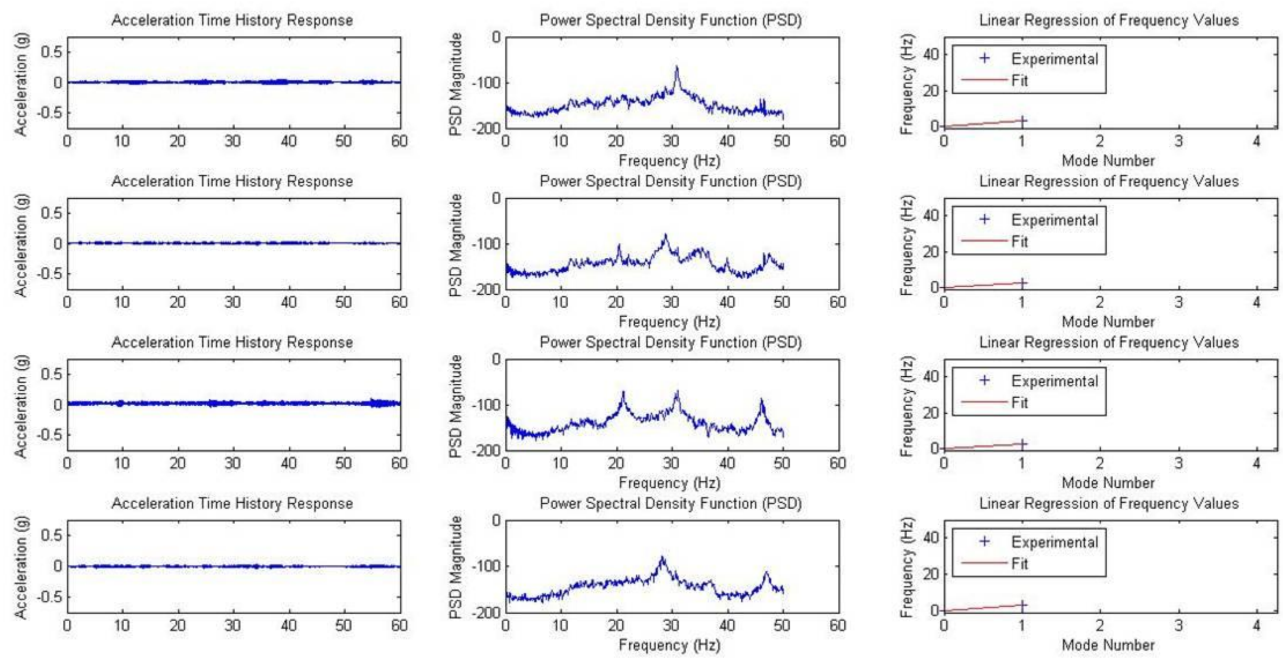
L16	w1 (Hz)	w2 (Hz)	w3 (Hz)	w4 (Hz)	wfit (Hz)	Norm of R	T (k)
1	6.31	12.86	19.56	25.97	6.52	0.20	43.51
2	6.41	12.96	19.37	25.77	6.45	0.08	42.60
3	6.90	13.79	21.13	28.81	7.18	0.55	52.84
4	6.55	13.60	20.35	27.44	6.87	0.27	48.27

Cable Set L17



L17	w1 (Hz)	w2 (Hz)	w3 (Hz)	w4 (Hz)	wfit (Hz)	Norm of R	T (k)
1	11.00	21.18			10.59	0.34	51.01
2	11.10	23.33	36.19		12.08	0.89	66.40
3	10.32	21.08	32.91		10.95	0.77	54.56
4	8.51	17.22	26.41	36.34	9.06	0.90	37.33

Cable Set L18



L18	w1 (Hz)	w2 (Hz)	w3 (Hz)	w4 (Hz)	wfit (Hz)	Norm of R	T (k)
1							
2							
3							
4							

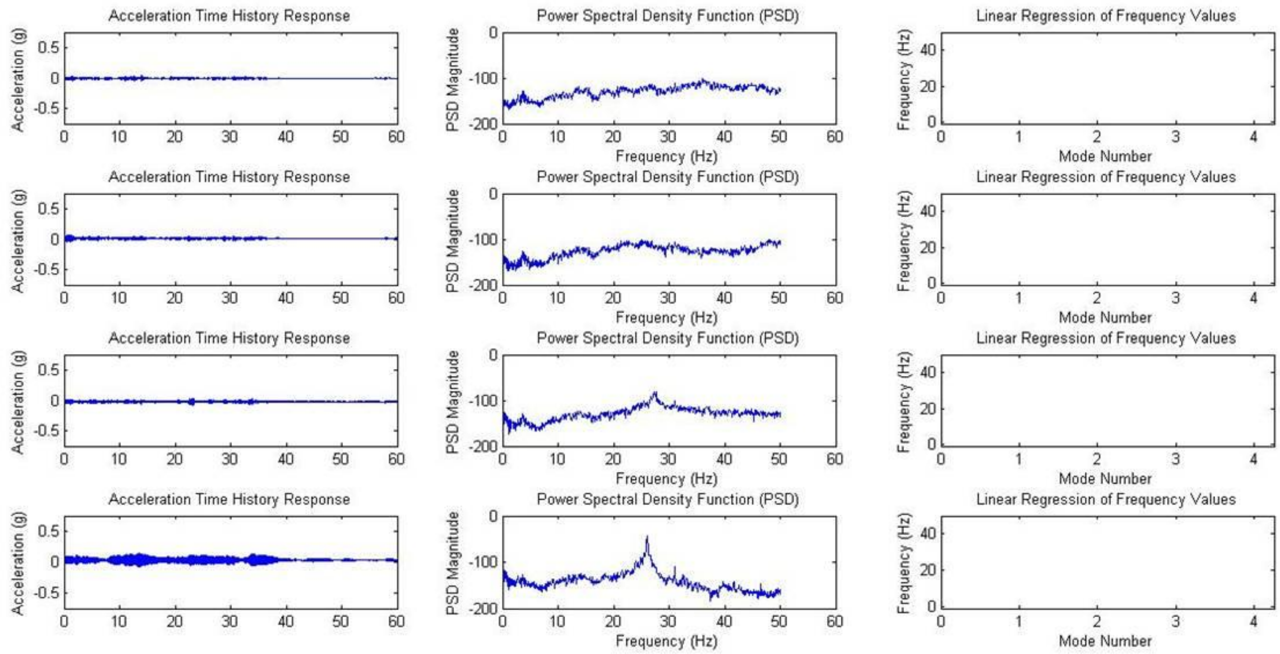
NORTH SPAN

During this portion of the testing, the sensors were applied in a different order compared to the original data. In order to be able to compare the cable behavior from the original and the south deck removed scenarios, the following information will make that possible. This problem has been resolved in the main body of the report and only occurs in this portion of Appendix C.

South Deck Removed → Original

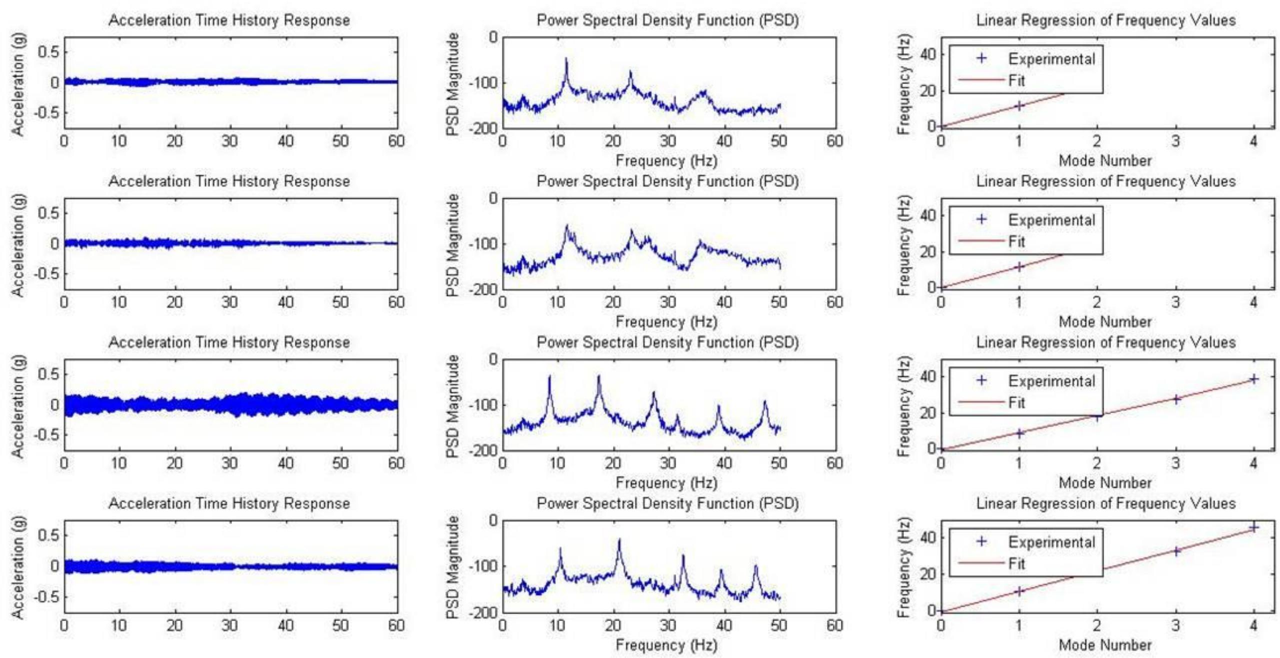
Cable 1	→	Cable 3
Cable 2	→	Cable 4
Cable 3	→	Cable 1
Cable 4	→	Cable 2

Cable Set L2N



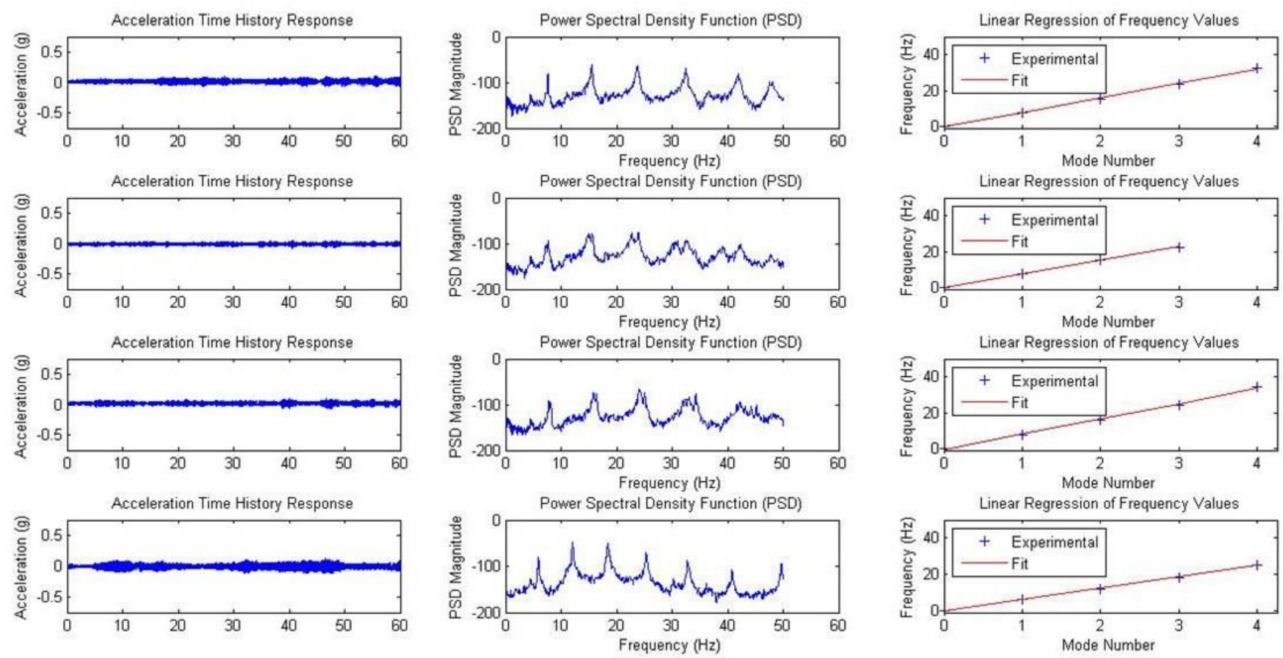
L2N	w1 (Hz)	w2 (Hz)	w3 (Hz)	w4 (Hz)	wfit (Hz)	Norm of R	T (k)
1							
2							
3							
4							

Cable Set L3N



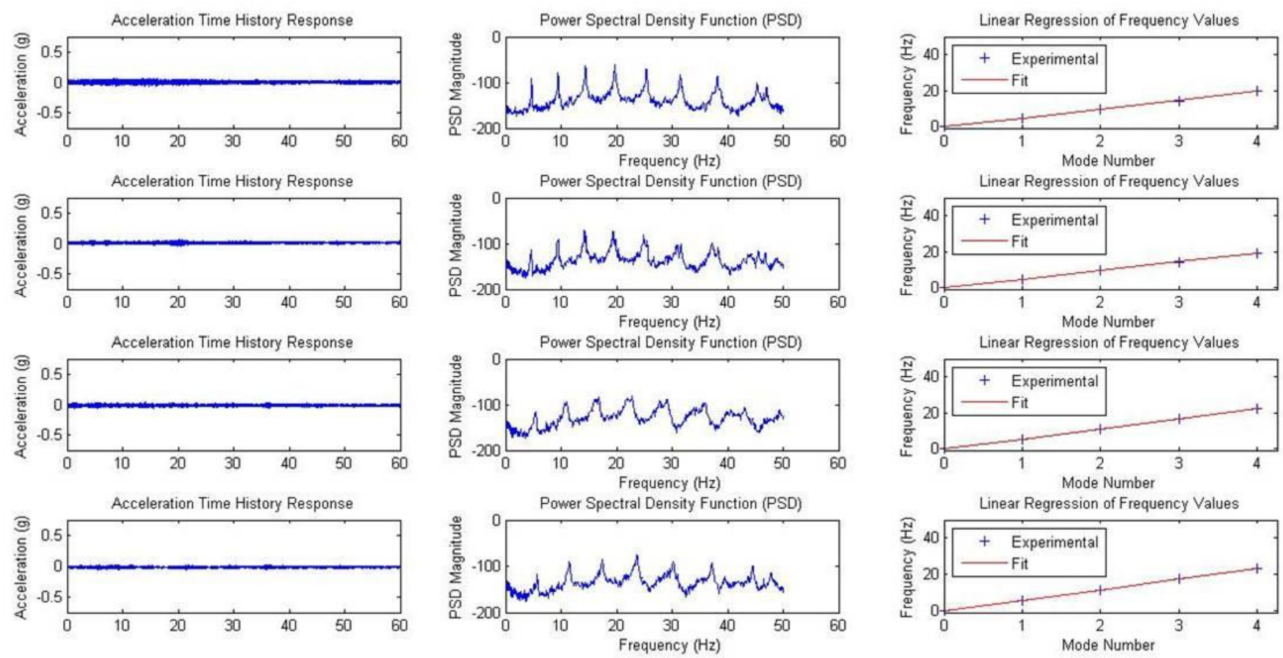
L3N	w1 (Hz)	w2 (Hz)	w3 (Hz)	w4 (Hz)	wfit (Hz)	Norm of R	T (k)
1	11.54	23.08			11.54	0.00	60.62
2	11.74	23.48			11.74	0.00	62.69
3	8.56	17.51	27.34	39.13	9.70	2.02	42.84
4	10.37	21.13	32.62	45.78	11.38	1.73	58.93

<u>Cable Set L4N</u>



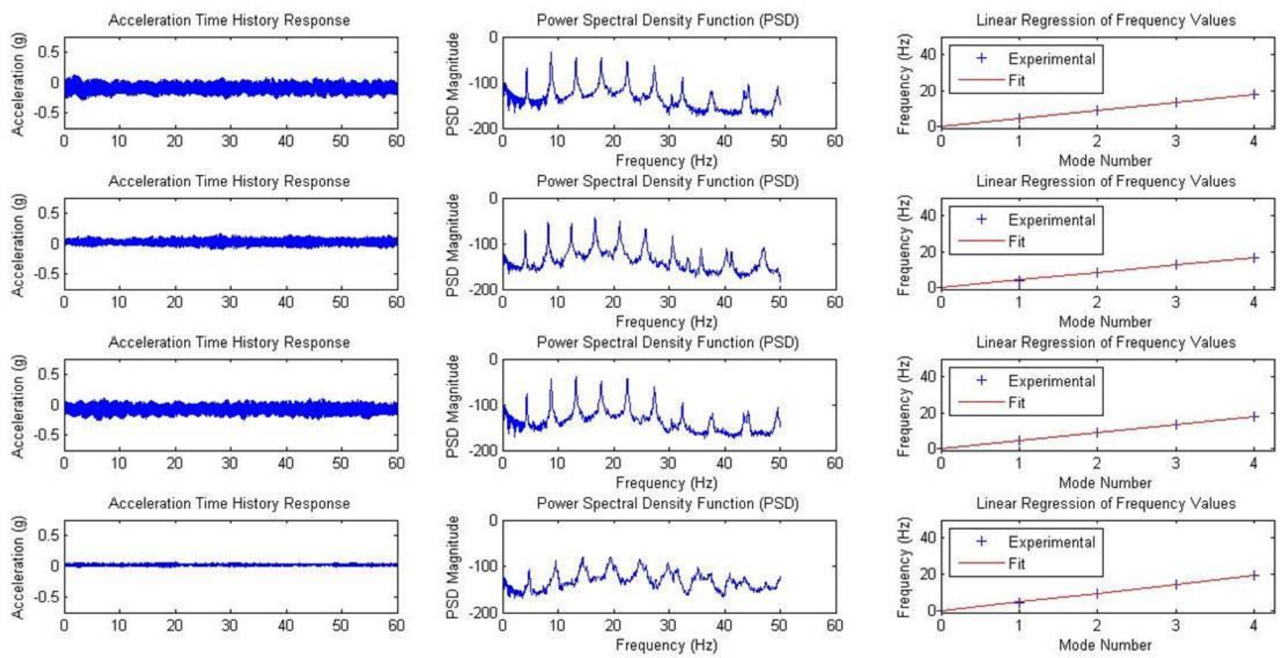
L4N	w1 (Hz)	w2 (Hz)	w3 (Hz)	w4 (Hz)	wfit (Hz)	Norm of R	T (k)
1	7.68	15.45	23.82	32.33	8.08	0.61	66.83
2	7.63	15.16	22.55		7.52	0.12	57.85
3	7.87	16.09	24.16	34.38	8.50	1.38	74.06
4	5.97	12.18	18.49	25.43	6.34	0.57	41.13

Cable Set L5N



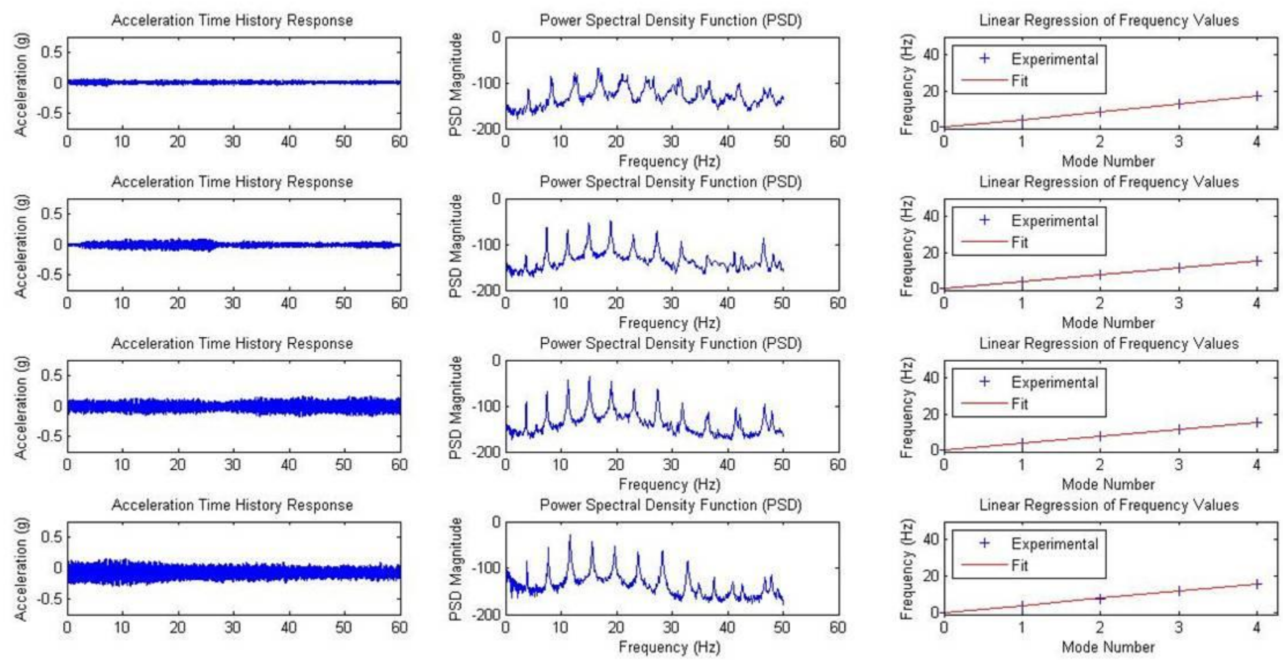
L5N	w1 (Hz)	w2 (Hz)	w3 (Hz)	w4 (Hz)	wfit (Hz)	Norm of R	T (k)
1	4.65	9.49	14.28	19.66	4.90	0.41	40.33
2	4.60	9.44	14.18	19.32	4.82	0.28	39.13
3	5.23	10.71	16.33	22.35	5.58	0.46	52.40
4	5.53	11.30	17.36	23.48	5.88	0.40	58.15

Cable Set L6N



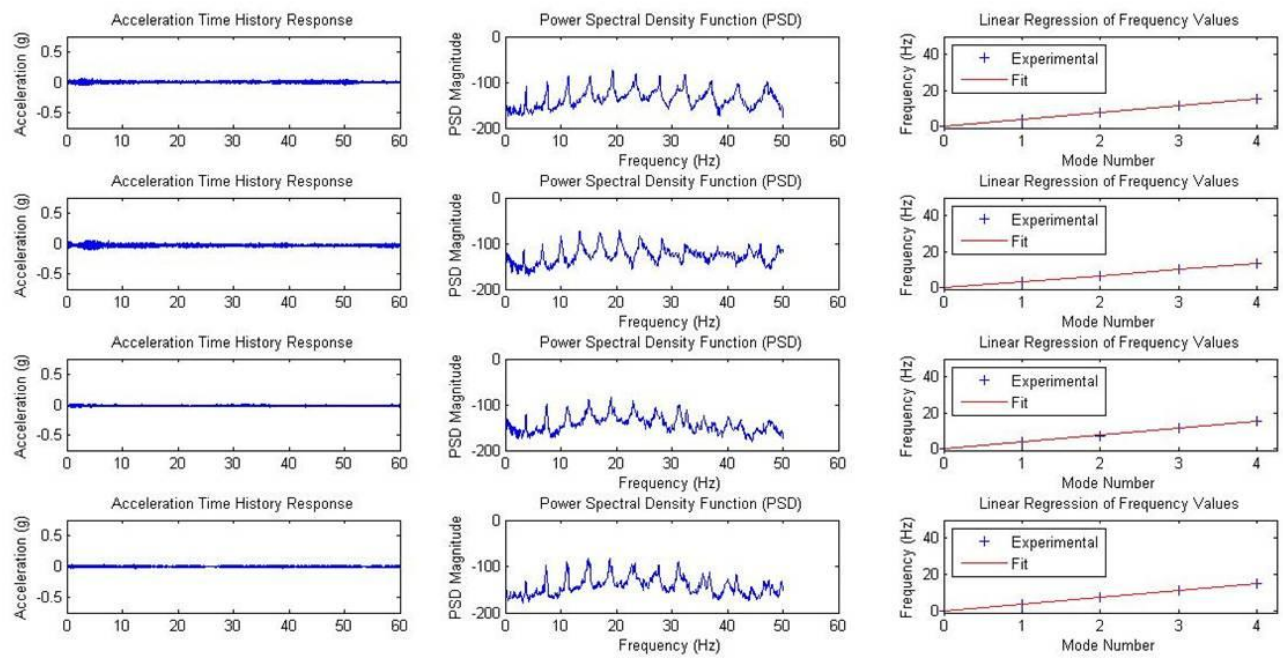
L6N	w1 (Hz)	w2 (Hz)	w3 (Hz)	w4 (Hz)	wfit (Hz)	Norm of R	T (k)
1	4.25	8.90	13.40	17.90	4.49	0.17	47.33
2	4.01	8.31	12.47	16.77	4.20	0.15	41.35
3	4.50	8.71	13.20	17.85	4.44	0.23	46.21
4	4.60	9.59	14.38	19.46	4.87	0.25	55.60

Cable Set L7N



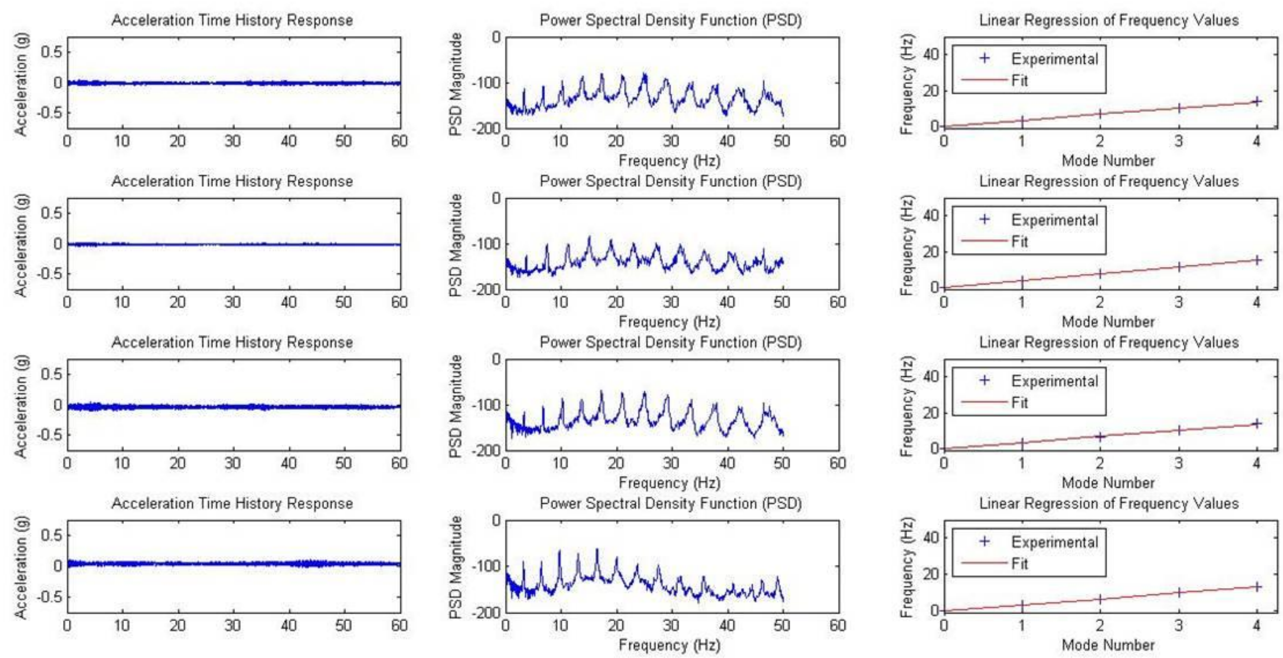
L7N	w1 (Hz)	w2 (Hz)	w3 (Hz)	w4 (Hz)	wfit (Hz)	Norm of R	T (k)
1	3.96	8.22	12.62	16.97	4.26	0.27	53.21
2	3.52	7.53	11.25	15.06	3.79	0.20	42.01
3	3.77	7.58	11.25	15.16	3.78	0.10	41.91
4	3.86	7.78	11.74	15.75	3.94	0.09	45.45

Cable Set L8N



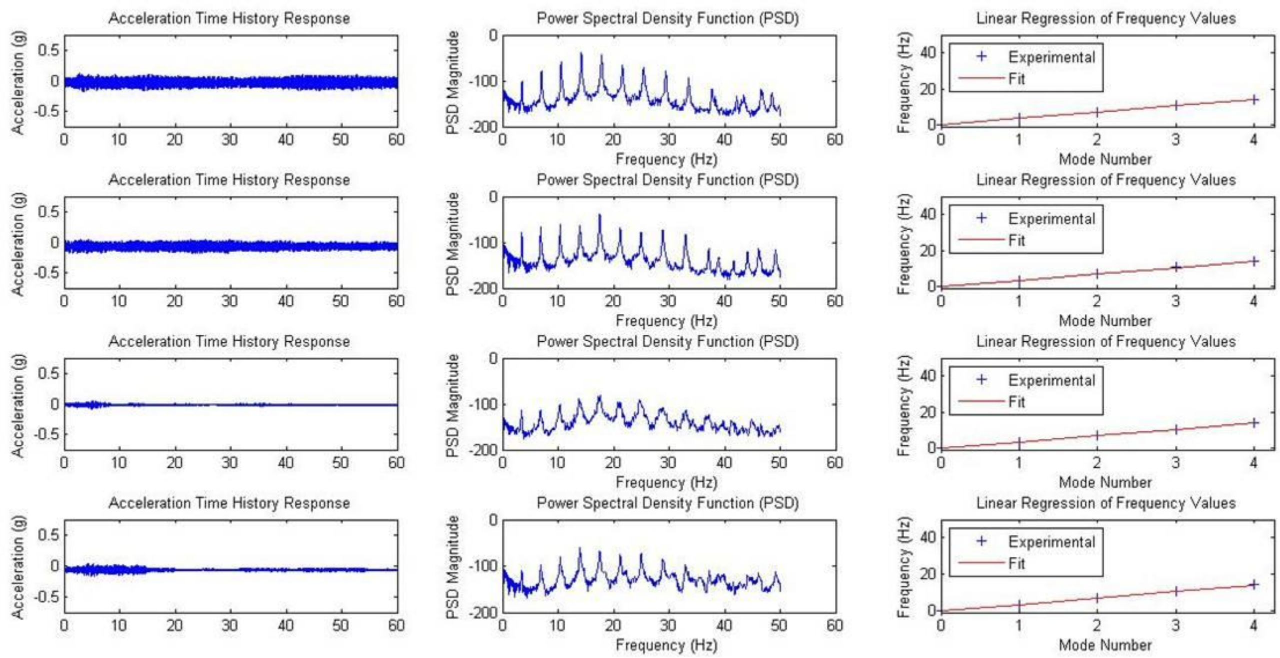
L8N	w1 (Hz)	w2 (Hz)	w3 (Hz)	w4 (Hz)	wfit (Hz)	Norm of R	T (k)
1	3.91	7.48	11.30	15.06	3.75	0.14	47.75
2	3.08	6.55	9.98	13.60	3.41	0.29	39.43
3	3.77	7.29	11.35	14.97	3.75	0.23	47.75
4	3.91	7.19	11.25	15.01	3.74	0.34	47.37

Cable Set L9N



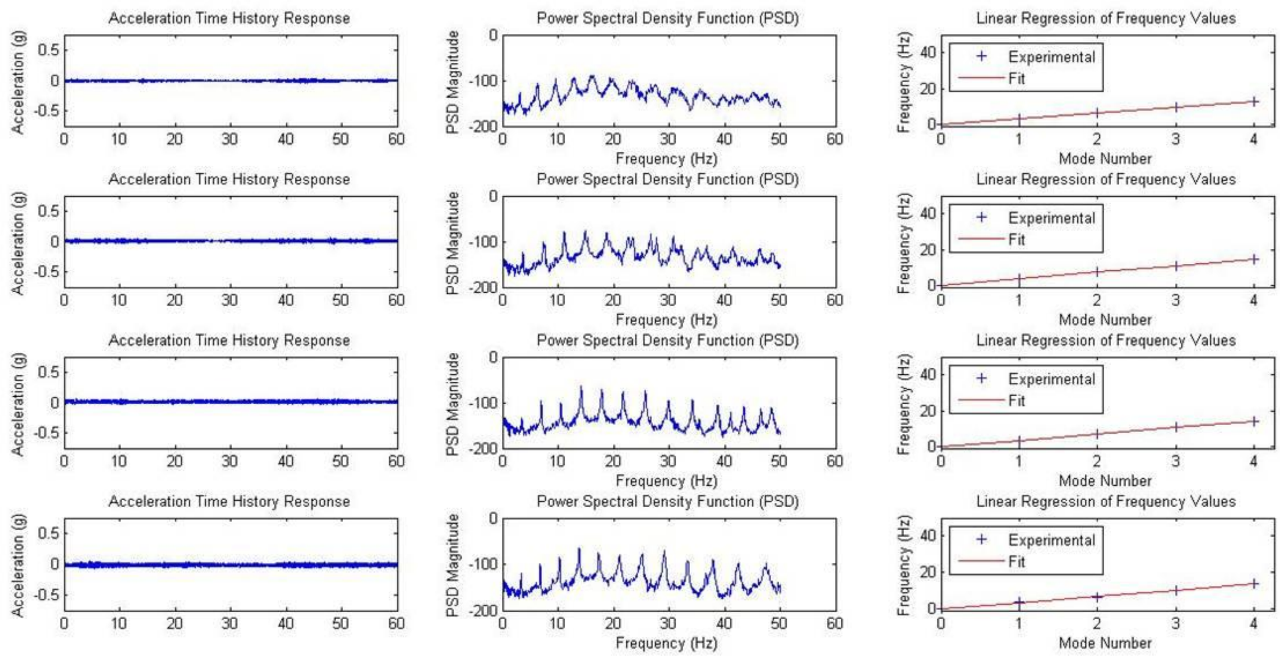
L9N	w1 (Hz)	w2 (Hz)	w3 (Hz)	w4 (Hz)	wfit (Hz)	Norm of R	T (k)
1	3.28	6.70	10.12	13.74	3.43	0.19	43.45
2	3.52	7.43	11.30	15.16	3.81	0.22	53.50
3	3.23	6.60	10.03	13.74	3.43	0.28	43.32
4	3.08	6.50	9.78	13.16	3.30	0.17	40.17

Cable Set L10N



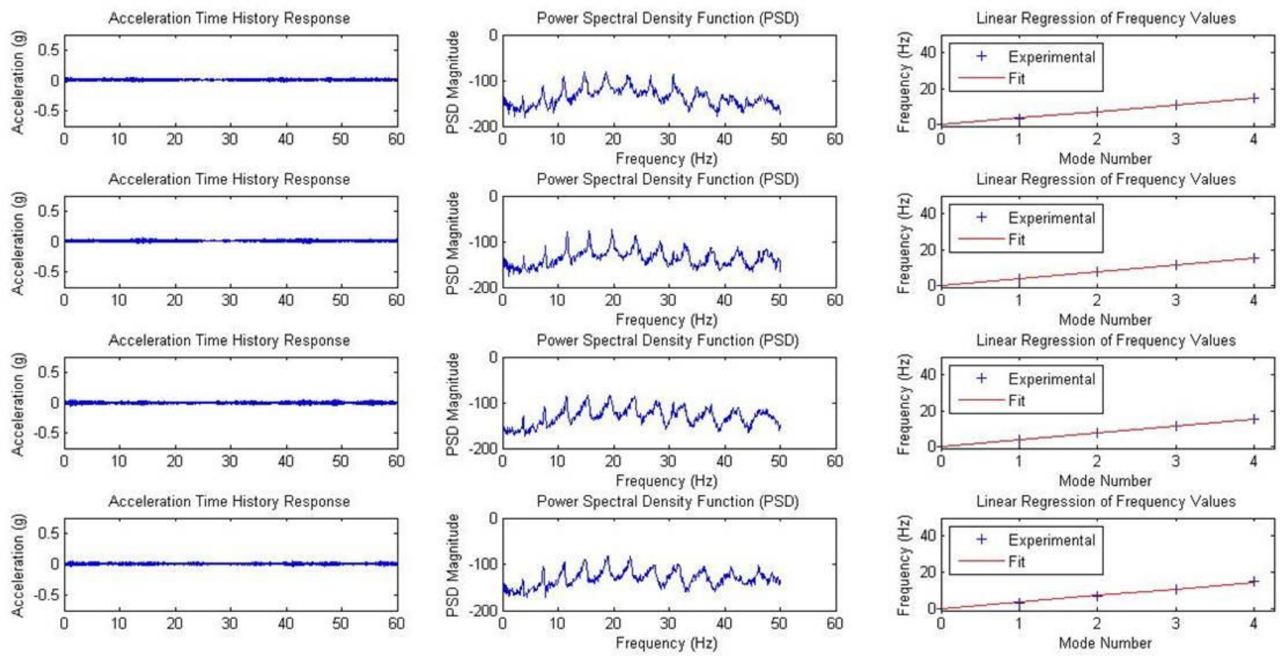
L10N	w1 (Hz)	w2 (Hz)	w3 (Hz)	w4 (Hz)	wfit (Hz)	Norm of R	T (k)
1	3.57	7.04	10.56	14.13	3.53	0.05	47.08
2	3.33	6.85	10.51	13.99	3.52	0.17	46.82
3	3.23	6.80	10.37	13.89	3.49	0.20	46.17
4	3.23	6.85	10.42	14.13	3.55	0.27	47.60

Cable Set L11N



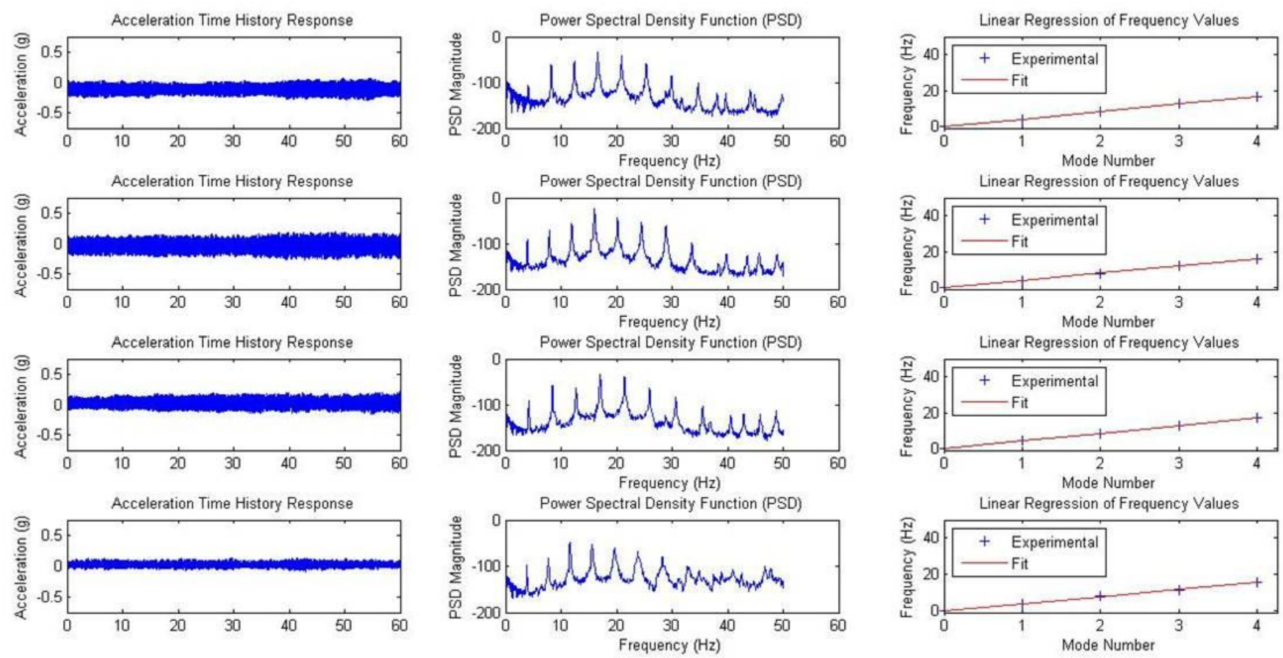
L11N	w1 (Hz)	w2 (Hz)	w3 (Hz)	w4 (Hz)	wfit (Hz)	Norm of R	T (k)
1	3.13	6.06	9.44	12.86	3.20	0.31	37.82
2	3.67	7.34	11.10	14.87	3.72	0.08	50.92
3	3.33	6.90	10.56	14.23	3.57	0.22	46.98
4	3.42	6.50	10.03	13.84	3.43	0.40	43.32

Cable Set L12N



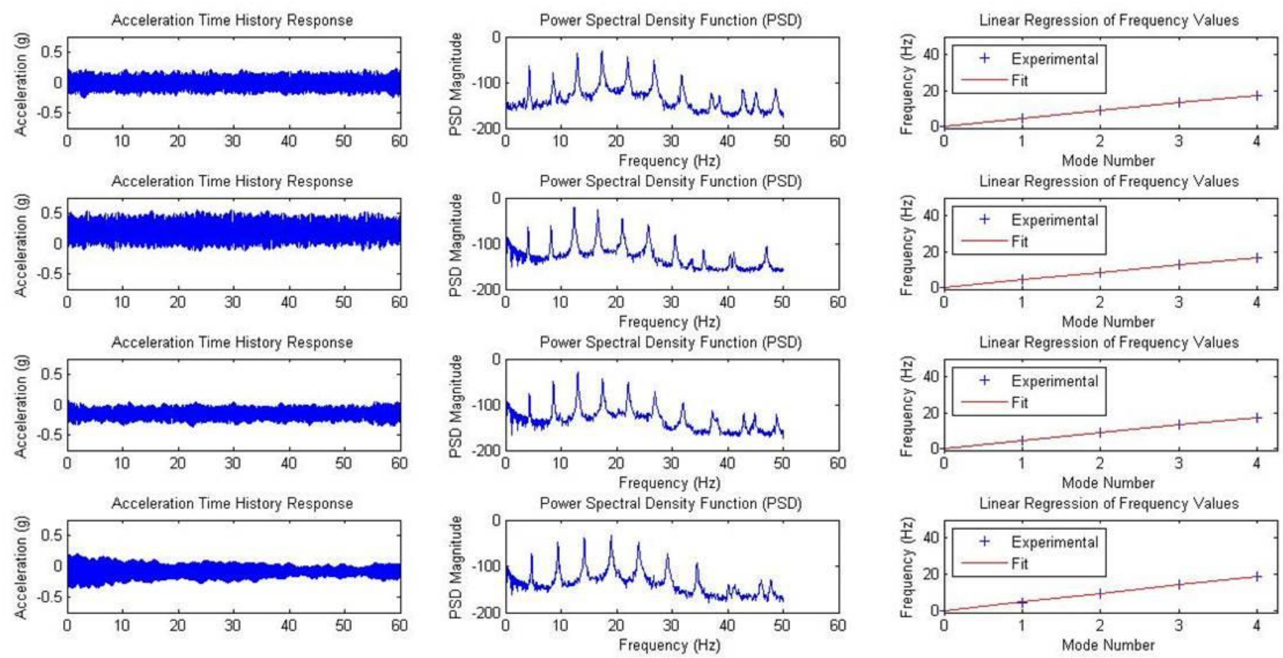
L12N	w1 (Hz)	w2 (Hz)	w3 (Hz)	w4 (Hz)	wfit (Hz)	Norm of R	T (k)
1	3.37	7.14	10.91	14.72	3.70	0.26	46.39
2	3.91	7.48	11.69	15.50	3.88	0.27	51.04
3	3.47	7.43	11.44	15.01	3.80	0.30	49.00
4	3.33	7.04	10.76	14.82	3.71	0.40	46.63

Cable Set L13N



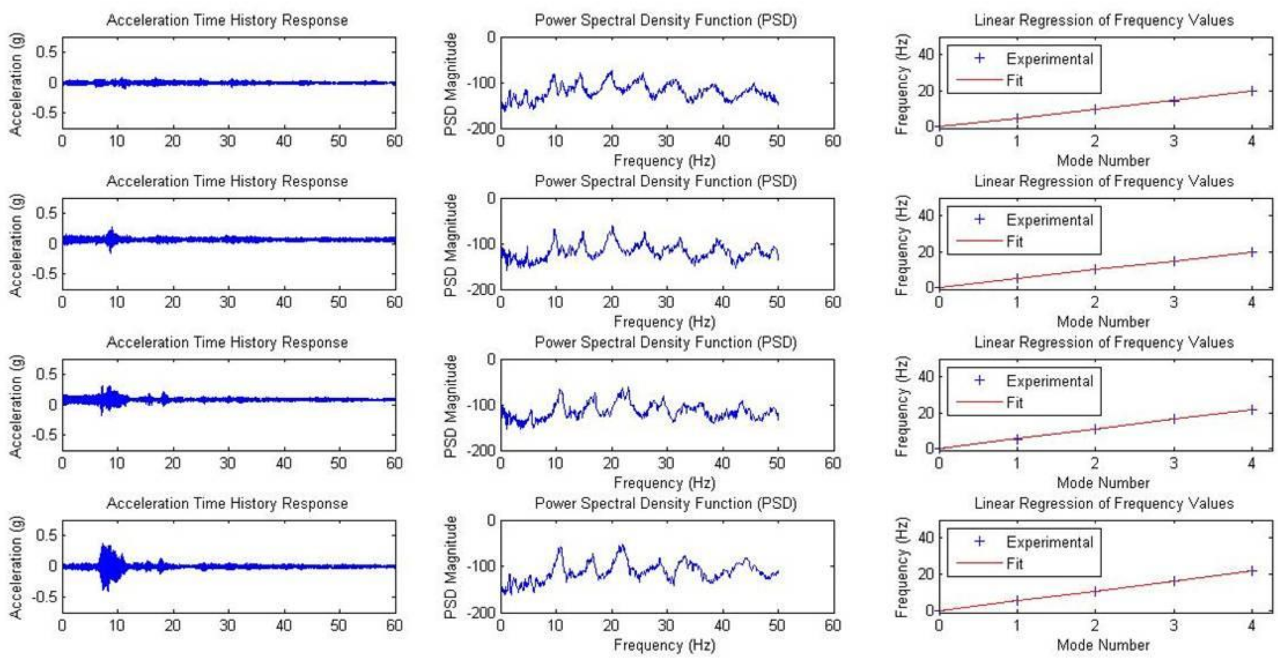
L13N	w1 (Hz)	w2 (Hz)	w3 (Hz)	w4 (Hz)	wfit (Hz)	Norm of R	T (k)
1	3.91	8.36	12.52	16.73	4.21	0.22	51.87
2	4.06	7.83	11.93	15.94	3.98	0.16	46.36
3	4.11	8.51	12.86	17.12	4.30	0.14	54.19
4	3.91	7.83	11.54	15.55	3.87	0.12	43.99

Cable Set L14N



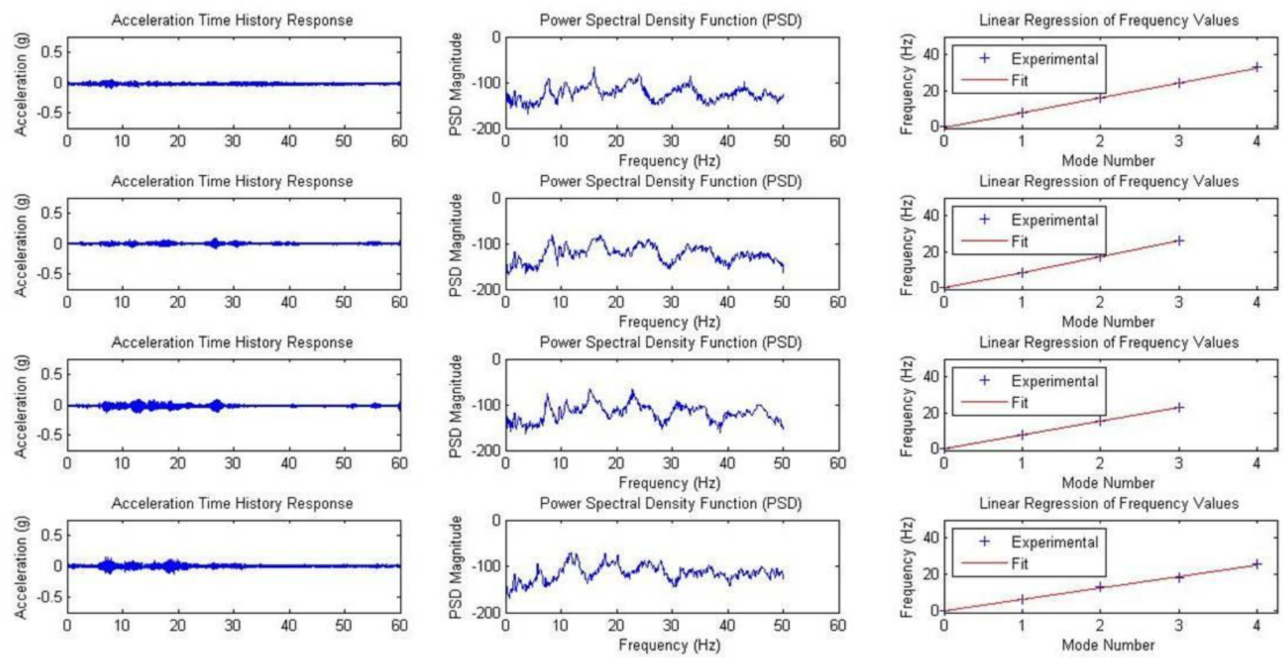
L14N	w1 (Hz)	w2 (Hz)	w3 (Hz)	w4 (Hz)	wfit (Hz)	Norm of R	T (k)
1	4.35	8.66	13.06	17.41	4.35	0.04	44.39
2	4.11	8.31	12.47	16.77	4.19	0.10	41.16
3	4.40	8.75	13.06	17.46	4.36	0.05	44.49
4	4.55	9.54	14.33	19.12	4.80	0.19	54.05

Cable Set L15N



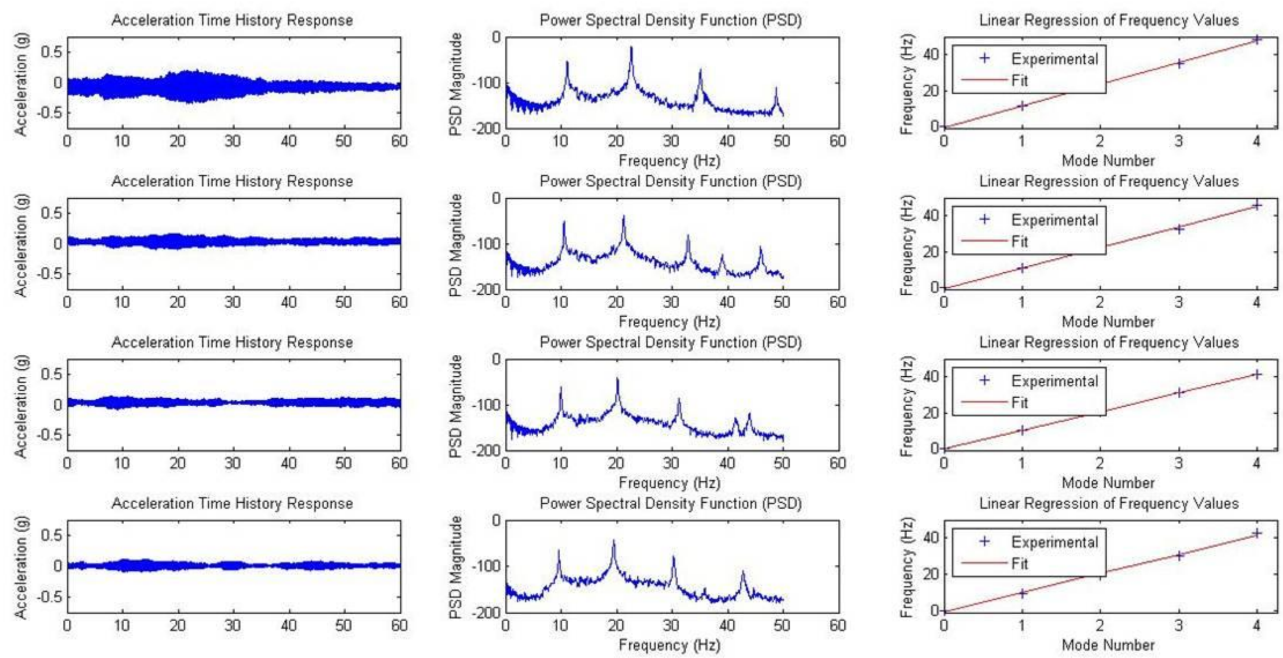
L15N	w1 (Hz)	w2 (Hz)	w3 (Hz)	w4 (Hz)	wfit (Hz)	Norm of R	T (k)
1	4.60	9.44	14.18	19.81	4.92	0.58	40.73
2	4.74	9.88	14.77	19.90	4.98	0.20	41.79
3	5.23	10.81	16.73	21.81	5.51	0.40	51.12
4	5.33	10.76	16.43	21.86	5.48	0.18	50.58

Cable Set L16N



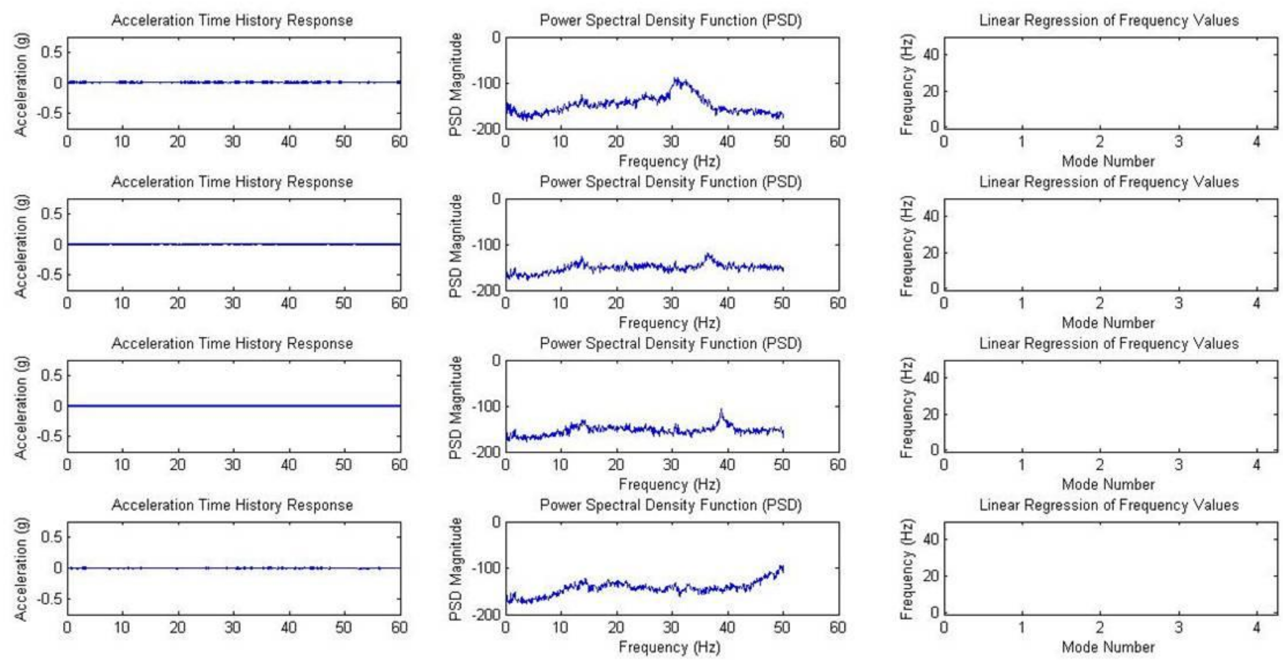
L16N	w1 (Hz)	w2 (Hz)	w3 (Hz)	w4 (Hz)	wfit (Hz)	Norm of R	T (k)
1	7.58	15.85	24.06	33.21	8.29	0.85	70.36
2	8.31	17.22	25.92		8.67	0.26	76.89
3	7.63	15.31	23.08		7.69	0.07	60.59
4	6.11	12.91	17.90	26.07	6.39	1.34	41.83

<u>Cable Set L17N</u>



L17N	w1 (Hz)	w2 (Hz)	w3 (Hz)	w4 (Hz)	wfit (Hz)	Norm of R	T (k)
1	11.25	22.74	35.11	48.66	12.12	1.49	66.83
2	10.51	21.23	32.77	45.97	11.42	1.72	59.34
3	10.07	20.30	31.35	41.42	10.41	0.51	49.33
4	9.49	19.42	30.22	42.94	10.66	2.02	51.72

Cable Set L18N



L18N	w1 (Hz)	w2 (Hz)	w3 (Hz)	w4 (Hz)	wfit (Hz)	Norm of R	T (k)
1							
2							
3							
4							