Field-Measured Natural Frequencies of the Delaware Memorial Bridge

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ABSTRACT

The Delaware Memorial Bridge is a major suspension bridge that is critical to the tri-state region of northern Delaware, southern New Jersey, and southeastern Pennsylvania. The Delaware Memorial Bridge consists of two nearly-identical suspension bridges (hence the nickname "Twin Spans") that cross the Delaware River from southern New Jersey to northern Delaware. Field ambient vibration measurements of Structures 1 and 2 of the Delaware Memorial Bridge were conducted in June 2001 and September 2003. These measurements were used to derive the natural frequencies and modes of vibration for these structures. These field-measured frequencies and modes were then compared with each other and with computer-generated natural frequencies and modes of vibration that were derived for Structure 2 of the Delaware Memorial Bridge in 1997. Specifically, the 2001 seismometer-generated results for Structure 1 are compared with the 2003 accelerometer-generated results for Structure 1, the 2003 field-measured results for Structure 2 were compared with the 2003 field-measured results for Structure 1, and the 2003 field-measured results for Structure 2 were compared with the 1997 computer-generated results for Structure 2. Overall, these three different types of comparisons indicated relatively good correlation for transverse motion, but only fair correlation for longitudinal and vertical motion.

INTRODUCTION

The Delaware Memorial Bridge consists of two nearly-identical suspension bridges that cross the Delaware River from Salem County in southern New Jersey to New Castle County in northern Delaware. Both structures are owned, operated, and maintained by the Delaware River and Bay Authority (DRBA). Structure 1 (the southern of the two structures) was completed in 1951, while Structure 2 (the northern of the two structures) was finished in 1968. Each structure has one 655.3-meter (2,150-foot) main suspension span and two 228.6-meter (750-foot) suspended side spans. In both structures, the suspended deck truss is attached at the main cable anchorages by connections that allow rotation about the transverse axis with no relative motion allowed in the longitudinal, transverse, or vertical directions. The suspended deck truss is attached at the towers by connections that allow rotation about the transverse axis and relative motion in the longitudinal direction only.

Structures 1 and 2 of the Delaware Memorial Bridge cross the Delaware River closer to the mouth of the river than any other bridges and as such they have the longest main spans of any bridges that cross the Delaware River. These structures provide the critical link that connects the southern end of the New Jersey Turnpike with Interstate Highway I-295. As such, these two structures are considered to be two of the most important bridge structures in the tri-state area of northern Delaware, southern New Jersey, and southeastern Pennsylvania along the I-95 corridor. Because of their size, location, and importance, Structures 1 and 2 of the Delaware Memorial Bridge are comparable to the Golden Gate Bridge at the entrance to San Francisco Bay, the Chesapeake Bay Bridge across the entrance to Chesapeake Bay, the Astoria Bridge at the mouth of the Columbia River, and the Verrazano Narrows Bridge across the mouth of the Hudson River.

FIELD AMBIENT VIBRATION ANALYSES

Field ambient vibration analyses are field vibration measurements that are taken using ambient traffic and wind loads as the dynamic input. Such analyses are much more practical for major river crossings where complete closure of the structure for controlled loading is not possible. Field ambient vibration analyses have been used to derive the natural frequencies and modes of vibration for a variety of structures including concrete and steel highway bridges (*1, 2, 3*) and suspension bridges (*4, 5, 6, 7, 8*). Thus, the state of the art of field ambient vibration analysis is well established and the procedures are well known.

Field Ambient Vibration Measurements

The goal in the field ambient vibration measurements that were conducted on Structures 1 and 2 of the Delaware Memorial Bridge and on other bridges over the Delaware River between 2001 and 2003 was to recover the fundamental or lowest-frequency modes for each direction of motion. The main objective of the measurements that were conducted on Structure 1 in 2001 was to test the seismometers that were purchased for field ambient vibration measurements of bridges in the Delaware Valley region. The main objective of the measurements that were conducted on Structures 1 and 2 in 2003 using triaxial accelerometers was to provide data that could be correlated with the 2001 field-measured results and with the 1997 computer-generated results (*9, 10*). In both 2001 and 2003,

measurements were taken during off-peak hours between 10 am and 2 pm with one lane of traffic closed for these measurements. The directions of motion measured were the longitudinal direction (horizontal and parallel to the centerline of the bridge), the transverse direction (horizontal and perpendicular to the centerline of the bridge), and the vertical direction. The 2001 data was sampled at 200 Hz., while the 2003 data was originally sampled at 2000 Hz. and was then decimated to a lower sampling frequency of 200 Hz. The decimation step involves lowpass filtering by a linear phase finite impulse response filter with 400 coefficients and a cutoff frequency of 100 Hz followed by subsampling by a factor of 10.

On June 14, 2001, faculty and students from the College of Engineering at Rowan University conducted field ambient vibration measurements on Structure 1 of the Delaware Memorial Bridge using Kinemetrics WR-1 seismometers with a frequency range of 0 to 20 Hz. The purpose of these measurements was to determine the natural frequencies of vibration for this structure and to test the seismometers that were being used for the first time for these measurements. Approximately one hour of acceleration records was taken for each seismometer and was stored on a laptop computer. These records were then analyzed at Rowan University.

For the 2001 measurements on Structure 1, the seismometers were placed on the bridge deck along the south curb of the southern-most traffic lane. The 2001 measurements were taken using six seismometers located at three points on the main suspended span of Structure 1 as shown in the plan sketch in Figure 1a. At midspan of the main span, three seismometers were set up and oriented in the longitudinal, transverse, and vertical directions. One seismometer was set up and oriented in the vertical direction at the east quarter point. At the east tower, two seismometers were set up and oriented in the transverse and vertical directions.

On September 30, 2003, faculty and students from the College of Engineering at Rowan conducted additional field ambient vibration measurements on Structures 1 and 2 of the Delaware Memorial Bridge using PCB Piezotronics series 3703 triaxial accelerometers with a frequency range of 0 to 800 Hz. The purpose of the measurements on Structure 1 was for comparison with the measurements conducted in 2001. The purpose of the measurements on Structure 2 was to determine the natural frequencies of vibration for this structure for comparison with Structure 1 and for comparison with finite-element computer analyses that were conducted on Structure 2 in 1997 *(9, 10)*. Approximately 20 minutes of acceleration records were taken for each accelerometer and stored on a laptop computer. These records were subsequently analyzed at Rowan University.

The 2003 measurements were taken using three tri-axial accelerometers with each accelerometer oriented with one axis in the longitudinal direction, one axis in the transverse direction, and one axis in the vertical direction at each location. One set of measurements was taken on Structure 1 and three sets of measurements were taken on Structure 2. For the 2003 measurements on Structure 1, the accelerometers used were placed on the bridge deck along the south curb of the southern-most traffic lane. For the 2003 measurements on Structure 2, the accelerometers used were placed on the bridge deck along the north curb of the northern-most traffic lane.

The first set of 2003 measurements (data set 1) was taken at the following locations on Structure 2 (Figure 1b): at midspan of the east suspended side span, at the east tower, and at the east quarter point of the main suspended span. The second set of 2003 measurements (data set 2) was taken at the following locations on Structure 2 (Figure 1b): at the east quarter point of the main suspended span, at midspan of the main suspended span, and at the west quarter point of the main suspended span. The third set of 2003 measurements (data set 3) was taken at the following locations on Structure 2 (Figure 1b): at the west quarter point of the main suspended span, at the west tower, and at midspan of the west suspended side span. The fourth and final set of 2003 measurements (data set 4) was taken at the following locations on the main suspended span of Structure 1 (Figure 1c): at midspan, at the east quarter point, and at the east tower. These locations for Structure 1 were the same locations used for field measurements in 2001.

The switch from seismometers to accelerometers for the 2001 versus 2003 field measurements was made because the seismometers were not sufficiently robust and were damaged during subsequent measurements on another bridge over the Delaware River in 2001. Thus, the seismometers had to be replaced by more-robust transducers for the subsequent measurements that were conducted on other bridges in 2002 and 2003, and for measurements that were conducted on the Delaware Memorial Bridge in 2003.

Laboratory Analyses

Laboratory analyses of the 2001 and 2003 field-measured records were conducted. For these laboratory analyses, the acceleration versus time record from each transducer was subjected to a fast Fourier transformation (FFT) and the resulting plots of acceleration amplitude versus frequency were derived for frequencies between 0.0 and 1.0 Hz. These FFT analysis plots were used to pinpoint the natural frequencies of vibration obtained from each transducer record. Modal plots were then generated for each modal frequency. While the measurements taken on Structure 1 in 2001 and 2003 were limited to the main suspended span, the three data sets that were measured on Structure 2 in 2003 were combined to form complete modal plots for both the main suspended span and the two suspended side spans.

As examples of the 2003 modal plots for Structure 2, Figures 2a and 2b show the first symmetric transverse mode and the first asymmetric transverse mode, respectively, while Figures 3a and 3b illustrate the first symmetric vertical mode and the first asymmetric vertical mode, respectively. In Figures 2 and 3, the vertical axis represents the modal amplitudes, which have been normalized such that the maximum modal amplitudes are either -1.0 or +1.0, while the horizontal axis represents the horizontal distances from the east anchorage of the main suspension cables. In addition in Figures 2 and 3, the rectangular icons represent the locations of the main suspension cable anchorages and towers, while the triangular icons represent the modal amplitudes at each location.

COMPUTER-GENERATED FREQUENCIES

As part of their report that was submitted to DRBA in August 1997 (*9*), Imbsen Consulting Engineer (ICE) presented frequency and modal results for Structure 2 of the Delaware Memorial Bridge based on finite-element modeling and modal analysis of this structure. Data was also presented in the paper by Thorkildsen and Wang (*10*). The software package used for these analyses was GTSTRUDL. The models developed were full three-dimensional models with lumped masses and including the deck, cables, and towers.

ICE presented two sets of frequency and modal analysis results for Structure 2: one set assuming that the foundation of Structure 2 is fixed and another set assuming that the foundation is flexible. For comparison purposes, the decision was made to use the modal analysis results for the finite-element model of Structure 2 with the foundation fixed. The authors felt that the ambient vibrations that were measured in 2003 were not sufficient to excite the flexible foundation of Structure 2. For the comparisons of the computer-generated frequencies of Structure 2 with the field-measured frequencies of Structure 2, only those 25 mode shapes (of the first 69 mode shapes) for Structure 2 that were designated in the ICE report as important based on the level of the mass participation factors were considered.

COMPARISONS OF FREQUENCY RESULTS

Modal matching was accomplished based on comparisons of both modal frequency and mode shape.

Structure 1 – 2001 versus 2003 Field-Measured Results

Tables 1, 2, and 3 present comparisons between the 2001 field-measured modal frequencies and mode shapes and the 2003 field-measured modal frequencies and mode shapes that were derived for Structure 1 in the longitudinal, transverse, and vertical directions, respectively. The 2003 measurements recovered many more longitudinal frequencies compared with the 2001 results (Table 1). Overall, 3 of 8 frequencies recovered in 2003 matched 2001 results within 3.7%. The lowest frequency recovered for the 2001 results was 0.165 Hz, while the lowest frequency recovered for the 2003 results was 0.108 Hz.

For the transverse direction (Table 2), a total of 11 symmetric modes and 3 asymmetric modes were recovered. The lack of any asymmetric modes for the 2001 results was a direct result of the fact that only one seismometer was oriented in the transverse direction for these measurements and since this seismometer was located at midspan, no asymmetric modes were recovered for the 2001 results. For the 11 symmetric modes, there were 5 matches within 3.7%. The 2001 measurements failed to recover 2 symmetric modes (0.102 and 0.123 Hz.) that were derived for the 2003 results, while the 2003 measurements failed to recover 4 symmetric modes (0.464 to 0.987 Hz.) that were derived for the 2001 results. The 2001 results tended to recover the higher frequency modes (0.4 to 1.0

Hz.), while the 2003 results tended to recover the lower frequency modes (0.0 to 0.5 Hz.). The lowest frequency recovered for the 2001 results was 0.093 Hz, while the lowest frequency recovered for the 2003 results was 0.095 Hz, which represents a difference of 2.2%.

For the vertical direction (Table 3), a total of 12 symmetric modes and 3 asymmetric modes were recovered. For the 12 symmetric modes, there were 4 matches within 1.5%. The 2001 results failed to recover 4 symmetric modes (0.114 to 0.239 Hz.) that were derived for the 2003 results, while the 2003 results failed to recover 4 symmetric modes (0.407 to 0.521 Hz.) that were derived for the 2001 results. For the 3 asymmetric modes, there were 2 matches within 0.6%. The 2001 results recovered all of the asymmetric modes, while the 2003 results failed to recover 1 symmetric mode (0.720 Hz.) that was derived for the 2001 results. The 2001 results tended to recover the higher frequency modes (0.3 to 1.0 Hz.), while the 2003 results tended to recover the lower frequency modes (0.0 to 0.4 Hz.). The lowest frequency recovered for the 2001 results was 0.165 Hz, while the lowest frequency recovered for the 2003 results was 0.114 Hz.

Structure 1 versus Structure 2 – 2003 Field-Measured Results

Tables 4, 5, and 6 present comparisons between the 2003 field-measured modal frequencies and mode shapes for Structures 1 and 2 in the longitudinal, transverse, and vertical directions, respectively. For the longitudinal direction (Table 4), the number of modes recovered was comparable for the Structure 1 measurements (8 modes recovered) versus the Structure 2 measurements (10 modes recovered). Overall, 6 of 12 frequencies recovered for Structure 1 matched the Structure 2 results within 7.1% with 4 matches within 1.3%. The lowest frequency recovered for the Structure 1 results was 0.108 Hz, while the lowest frequency recovered for the 2003 results was 0.071 Hz.

For the transverse direction (Table 5), a total of 9 symmetric modes and 3 asymmetric modes were recovered. For the 9 symmetric modes, there were 6 matches within 7.3% with 4 matches within 4.0%. The Structure 1 measurements failed to recover 2 symmetric modes (0.174 and 0.544 Hz.) that were derived for Structure 2, while the Structure 2 measurements failed to recover 1 symmetric mode (0.102 Hz.) that was derived for Structure 1. For the 3 asymmetric modes, there were 2 matches within 4.6%. The Structure 1 measurements recovered all 3 asymmetric modes, while the Structure 2 measurements failed to recover 1 asymmetric mode (0.226 Hz.) that was derived for Structure 1. The lowest frequency recovered for Structure 1 was 0.095 Hz, while the lowest frequency recovered for Structure 2 was 0.092 Hz, which represents a difference of 3.2%.

For the vertical direction (Table 6), a total of 12 symmetric modes and 4 asymmetric modes were recovered. For the 12 symmetric modes, there were 4 matches within 1.1%. The Structure 1 results failed to recover 4 symmetric modes (0.267 to 0.858 Hz.) that were derived for Structure 2, while the Structure 2 results failed to recover 4 symmetric modes (0.114 to 0.239 Hz.) that were derived for Structure 1. For the 4 asymmetric modes, there were no matches. The Structure 1 results failed to recover 2 asymmetric modes (0.070 and 0.707 Hz.) that were recovered for Structure 2, while the Structure 2 results failed to recover 2 asymmetric modes (0.165 and 0.361 Hz.) that were derived for Structure 1. The lowest frequency recovered for the Structure 1 results was 0.114 Hz, while the lowest frequency recovered for the Structure 2 results was 0.070 Hz.

Structure 2 – 1997 Computer-Generated Results versus 2003 Field-Measured Results

Tables 7, 8, and 9 present comparisons between the 1997 computer-generated modal frequencies and mode shapes and the 2003 field-measured modal frequencies and mode shapes that were derived for Structure 2 in the longitudinal, transverse, and vertical directions, respectively. The 2003 measurements recovered many more longitudinal frequencies compared with the 1997 computer-generated results (Table 7). Overall, 5 of 10 frequencies recovered in 2003 matched 2001 results within 47.0% with 4 matches within 8.6% and 2 matches within 1.2%. The lowest frequency recovered for the 1997 computer-generated results was 0.134 Hz, while the lowest frequency recovered for the 2003 field-measured results was 0.071 Hz.

For the transverse direction (Table 8), a total of 12 symmetric modes, 2 asymmetric modes, and 4 unspecified modes were recovered. For the 12 symmetric modes, there were 4 matches within 18.0% with 3 matches within 5.0% and 2 matches within 1.3%. The 1997 computer-generated results failed to recover 4 symmetric modes (0.130 to 0.665 Hz.) that were derived for the 2003 field-measured results, while the 2003 measurements failed to recover 4 symmetric modes (0.290 to 0.933 Hz.) that were derived for the 1997 results. For

the 2 asymmetric modes and the 4 unspecified modes, there were no matches. The 1997 results failed to recover either of the asymmetric modes (0.246 and 0.271 Hz.), while the 2003 measurements failed to recover the 4 unspecified modes (0.675 to 0.854 Hz.) that were derived for the 1997 results. The 1997 results tended to recover the higher frequency modes (0.3 to 1.00 Hz.), while the 2003 measurements tended to recover the lower frequency modes (0.0 to 0.6 Hz.). The lowest frequency recovered for the 1997 results was 0.078 Hz, while the lowest frequency recovered for the 2003 measurements was 0.095 Hz, which represents a difference of 18.0%.

For the vertical direction (Table 9), the modes recovered included a total of 8 symmetric modes, 4 asymmetric modes, and 1 unspecified mode. For the 8 symmetric modes, there were 5 matches within 6.8%. The 1997 computer-generated results failed to recover 3 symmetric modes (0.260 to 0.903 Hz.) that were derived for the 2003 field-measured results, while the 2003 results recovered all of the symmetric modes. For the 4 asymmetric modes, there were 2 matches within 47.8% and 1 match within 8.4%. The 1997 results recovered all of the asymmetric modes, while the 2003 measurements failed to recover 2 asymmetric modes (0.189 and 0.257 Hz.) and the 1 unspecified mode (0.793 Hz.) that were derived for the 1997 results. The lowest frequency recovered for the 1997 results was 0.134 Hz, while the lowest frequency recovered for the 2003 measurements was 0.070 Hz.

CONCLUSIONS

In comparing the 2001 versus 2003 field-measured results for Structure 1, the major difference is in the range of frequencies recovered. The seismometers that were used in 2001 seemed to recover the higher-frequency results more effectively, while the accelerometers that were used in 2003 seemed to recover the lower-frequency results more effectively. The goal in the measurements that were conducted on Structures 1 and 2 of the Delaware Memorial Bridge and on other bridges over the Delaware River was to recover the fundamental or lowest-frequency modes for each direction of motion. Thus, the accelerometers proved to be much more effective for these low-frequency measurements.

In comparing the 2003 field-measured results for Structures 1 and 2, much of the difference would appear to be due to the differences between the two structures. Structure 2 has a slightly wider bridge deck with slightly larger truss members and bridge mass (differences of less than 10%) compared with Structure 1. The results in the transverse direction are relatively close with the differences most likely due to the differences in truss member sizes and bridge mass. While the number of modes recovered for Structures 1 and 2 are comparable in the longitudinal direction (8 versus 10, respectively) and the vertical direction (10 versus 10, respectively), the differences in the results are harder to explain. These differences may be due to three sources. The first source may be the differences in the expansion joints and bearings at the anchorages and towers. These differences in expansion joints and bearings could be differences in design details or differences in existing conditions. The second source for the differences between Structures 1 and 2 in the longitudinal and vertical directions may be the differences in the sizes of the truss members and the bridge mass. The third source for the differences between Structures 1 and 2 in the longitudinal and vertical directions may be the fact that the Structure 1 results were based on one set of bridge measurements on the main span, while the Structure 2 results were based on three sets of bridge measurements on the main and side spans. Thus, the responses of the side spans may not be adequately represented in the Structure 1 responses.

In comparing the 1997 computer-generated results versus the 2003 field-measured results for Structure 2, there appear to be two major differences. In the longitudinal and vertical directions, the model appears to be less flexible compared with the actual structure. Thus, the higher fundamental longitudinal and vertical frequencies of the model (both 0.134 Hz.) versus the actual structure (0.071 Hz. and 0.070 Hz., respectively). In the transverse direction, the computer model appears to be more flexible compared with the actual structure. Hence, the lower fundamental transverse frequency of the model (0.078 Hz.) versus the actual structure (0.092 Hz.).

The comparison between the 1997 computer-generated transverse results and the 2003 field-measured transverse results for Structure 2 of the Delaware Memorial Bridge (Table 8) is very similar to the results generated for the Bronx-Whitestone Bridge (*9, 10*). For the Bronx-Whitestone Bridge, the fundamental frequency for transverse motion derived by finite-element modeling and modal analysis was 0.091 Hz, which is 17.3% less than the fundamental transverse frequency derived by field ambient vibration analysis of the bridge, which was 0.110 Hz. As shown in Table 8 and as noted above, the fundamental frequency for transverse motion derived by finite-element modeling and modal analysis of Structure 2 of the Delaware Memorial Bridge was 0.078 Hz, which is 15.2% less

than the corresponding field-measured value for Structure 2, which was 0.092 Hz. Thus, for both the Bronx-Whitestone Bridge and Structure 2 of the Delaware Memorial Bridge, the computer models seem to be more flexible than the actual structures with respect to transverse motion.

The work presented herein compares frequency and modal results generated for the same suspension bridge structure (Structure 1) using two different types of transducers, for two different but very similar suspension bridge structures (Structures 1 and 2), and for the same structure (Structure 2) using field measurements versus computer modeling. These comparisons are all made on a major suspension bridge that is of critical importance to the regional tri-state transportation network of northern Delaware, southern New Jersey, and southeastern Pennsylvania.

FUTURE WORK

Future work will involve comparisons of the data generated for Structures 1 and 2 of the Delaware Memorial Bridge with the field-ambient vibration analysis results that have been generated for other suspension bridges that cross the Delaware River (based on results that have yet to be published) and for other suspension bridges across the United States (based on previously-published results). Future work will also involve comparisons of natural frequency and modal results for deck truss spans in the Delaware Memorial Bridge compared with frequency and modal results for deck truss spans in other bridges over the Delaware River (based on results that have not yet been published).

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```
                    Legend
          o = vertical seismometer locations
         | = transverse seismometer locations
        – = longitudinal seismometer locations

 west          west                                        east          east
anchor         tower                                       tower         anchor
   ┌──────────────┬──────────────────────────────────────────┬──────────────┐
   │              │                                          │              │
   │              │                                          │              │
   │              │                    |                     |              │
   │              │                    o -       o           o              │
   └──────────────┴──────────────────────────────────────────┴──────────────┘
   west side span                 main span                 east side span
```

a) 2001 Seismometer Locations on Structure 1

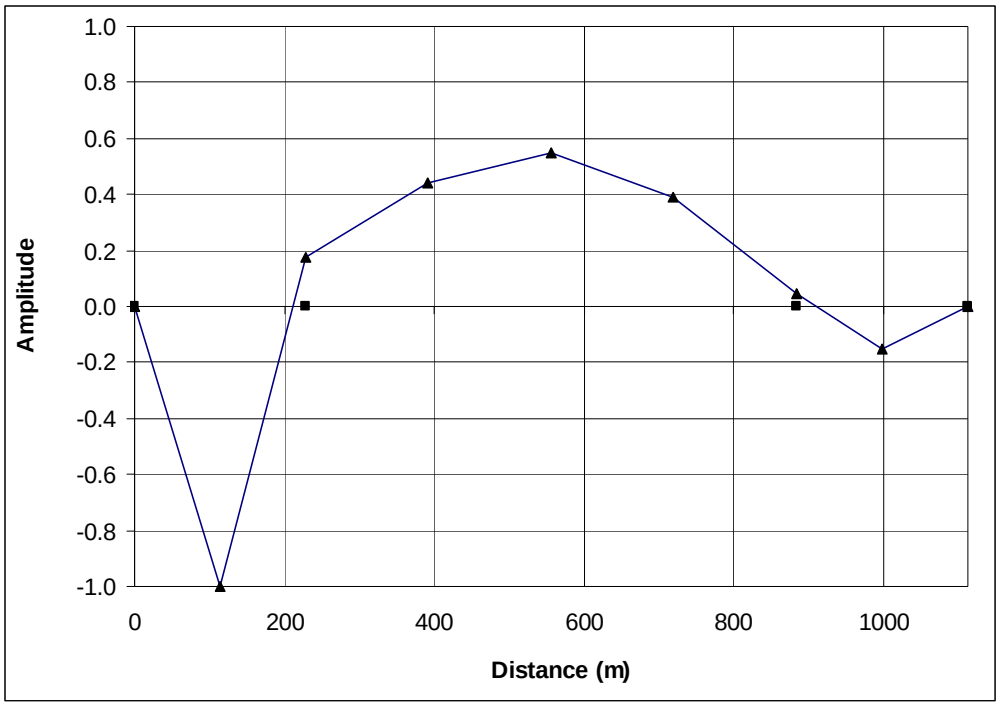
```
                    Legend
        + = triaxial accelerometer locations
                   1 = data set 1
                   2 = data set 2
                   3 = data set 3

                          2         2         2
        3       3         3                   1         1       1
   ┌──────────────┬──────────────────────────────────────────┬──────────────┐
   │       +      │+         +         +         +         +│      +       │
   │              │                                          │              │
   │              │                                          │              │
   │              │                                          │              │
   └──────────────┴──────────────────────────────────────────┴──────────────┘
 west          west                                        east          east
anchor         tower                                       tower         anchor

   west side span                 main span                 east side span
```

b) 2003 Accelerometer Locations on Structure 2

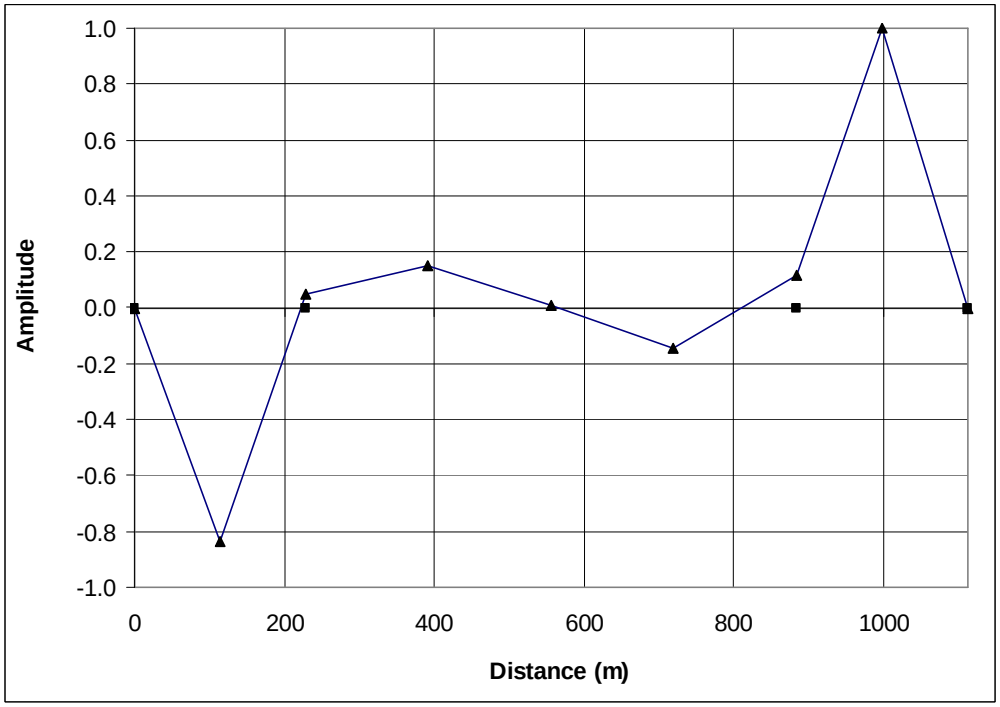
```
                    Legend
        + = triaxial accelerometer locations

 west          west                                        east          east
anchor         tower                                       tower         anchor
   ┌──────────────┬──────────────────────────────────────────┬──────────────┐
   │              │                                          │              │
   │              │                                          │              │
   │              │                                          │              │
   │              │                    +         +         +│              │
   └──────────────┴──────────────────────────────────────────┴──────────────┘
   west side span                 main span                 east side span
```

c) 2003 Accelerometer Locations on Structure 1

FIGURE 1 Plan Sketches of Transducer Locations for the Delaware Memorial Bridge

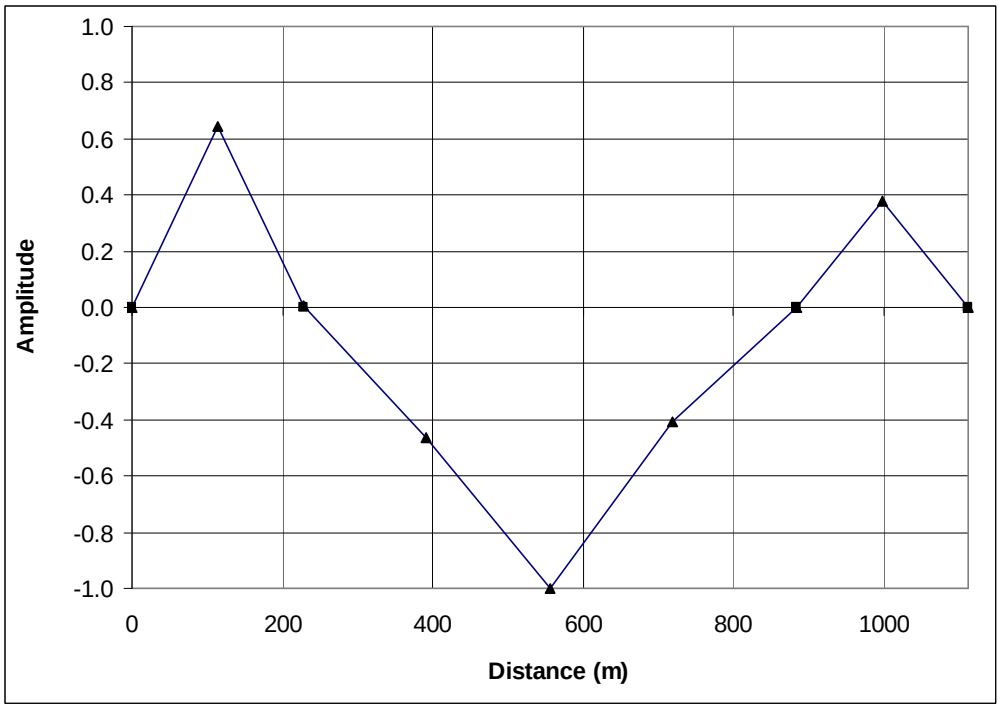


a) First Symmetric Mode

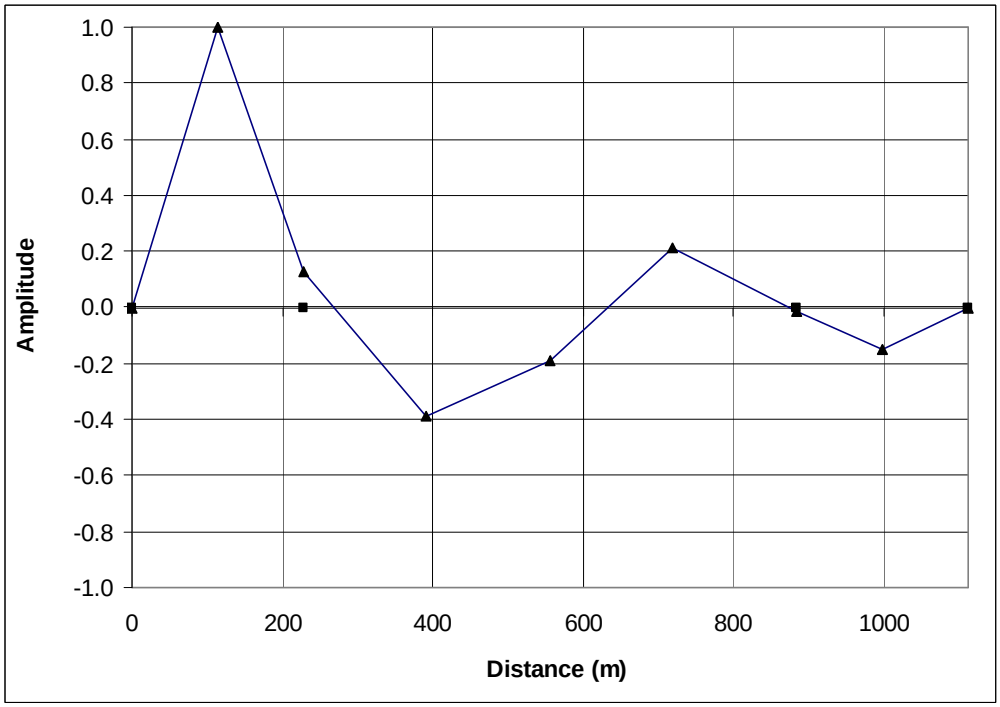


b) First Asymmetric Mode

FIGURE 2 2003 Field Measurements – Structure 2 Transverse Modes



a) First Symmetric Mode



b) First Asymmetric Mode

FIGURE 3 2003 Field Measurements – Structure 2 Vertical Modes

TABLE 1 Structure 1 Field-Measured Longitudinal Modes – 2001 versus 2003

Field-Measured Modes - 2001		Field-Measured Modes - 2003		Percent Difference
Modal Description	Frequency, (Hz.)	Modal Description	Frequency, (Hz.)	
NA	NA	First Longitudinal Mode	0.108	NA
First Longitudinal Mode	0.165	Second Longitudinal Mode	0.164	-0.6%
NA	NA	Third Longitudinal Mode	0.174	NA
NA	NA	Fourth Longitudinal Mode	0.264	NA
NA	NA	Fifth Longitudinal Mode	0.385	NA
NA	NA	Sixth Longitudinal Mode	0.589	NA
Second Longitudinal Mode	0.677	Seventh Longitudinal Mode	0.652	-3.7%
Third Longitudinal Mode	0.788	Eighth Longitudinal Mode	0.773	-1.9%

TABLE 2 Structure 1 Field-Measured Transverse Modes – 2001 versus 2003

Field-Measured Modes - 2001		Field-Measured Modes - 2003		Percent Difference
Modal Description	Frequency, (Hz.)	Modal Description	Frequency, (Hz.)	
First Symmetric Mode	0.093	First Symmetric Mode	0.095	2.2%
NA	NA	Second Symmetric Mode	0.102	NA
NA	NA	Third Symmetric Mode	0.123	NA
NA	NA	First Asymmetric Mode	0.226	NA
NA	NA	Second Asymmetric Mode	0.243	NA
NA	NA	Third Asymmetric Mode	0.259	NA
Second Symmetric Mode	0.407	Fourth Symmetric Mode	0.395	-3.0%
Third Symmetric Mode	0.432	Fifth Symmetric Mode	0.448	3.7%
Fourth Symmetric Mode	0.464	NA	NA	NA
Fifth Symmetric Mode	0.505	Sixth Symmetric Mode	0.505	0.0%
Sixth Symmetric Mode	0.521	NA	NA	NA
Seventh Symmetric Mode	0.662	Seventh Symmetric Mode	0.664	0.3%
Eighth Symmetric Mode	0.800	NA	NA	NA
Ninth Symmetric Mode	0.987	NA	NA	NA

TABLE 3 Structure 1 Field-Measured Vertical Modes – 2001 versus 2003

Field-Measured Modes - 2001		Field-Measured Modes - 2003		Percent Difference
Modal Description	Frequency, (Hz.)	Modal Description	Frequency, (Hz.)	
NA	NA	First Symmetric Mode	0.114	NA
NA	NA	Second Symmetric Mode	0.121	NA
NA	NA	Third Symmetric Mode	0.137	NA
First Asymmetric Mode	0.165	First Asymmetric Mode	0.165	0.0%
First Symmetric Mode	0.177	Fourth Symmetric Mode	0.175	-1.1%
NA	NA	Fifth Symmetric Mode	0.239	NA
Second Symmetric Mode	0.262	Sixth Symmetric Mode	0.259	-1.1%
Second Asymmetric Mode	0.363	Second Asymmetric Mode	0.361	-0.6%
Third Symmetric Mode	0.407	NA	NA	NA
Fourth Symmetric Mode	0.432	NA	NA	NA
Fifth Symmetric Mode	0.464	NA	NA	NA
Sixth Symmetric Mode	0.521	NA	NA	NA
Seventh Symmetric Mode	0.548	Seventh Symmetric Mode	0.540	-1.5%
Third Asymmetric Mode	0.720	NA	NA	NA
Eighth Symmetric Mode	0.914	Eighth Symmetric Mode	0.912	-0.2%

TABLE 4 2003 Field-Measured Longitudinal Modes – Structure 1 versus Structure 2

Structure 1 - Field-Measured Modes		Structure 2 - Field-Measured Modes		Percent Difference
Modal Description	Frequency, (Hz.)	Modal Description	Frequency, (Hz.)	
NA	NA	First Longitudinal Mode	0.071	NA
First Longitudinal Mode	0.108	NA	NA	NA
Second Longitudinal Mode	0.164	NA	NA	NA
Third Longitudinal Mode	0.174	Second Longitudinal Mode	0.174	0.0%
NA	NA	Third Longitudinal Mode	0.260	NA
Fourth Longitudinal Mode	0.264	Fourth Longitudinal Mode	0.266	0.8%
NA	NA	Fifth Longitudinal Mode	0.362	NA
Fifth Longitudinal Mode	0.385	Sixth Longitudinal Mode	0.380	-1.3%
Sixth Longitudinal Mode	0.589	Seventh Longitudinal Mode	0.547	-7.1%
Seventh Longitudinal Mode	0.652	Eighth Longitudinal Mode	0.649	-0.5%
NA	NA	Ninth Longitudinal Mode	0.667	NA
Eighth Longitudinal Mode	0.773	Tenth Longitudinal Mode	0.725	-6.2%

TABLE 5 2003 Field-Measured Transverse Modes – Structure 1 versus Structure 2

Structure 1 - Field-Measured Modes		Structure 2 - Field-Measured Modes		Percent Difference
Modal Description	Frequency, (Hz.)	Modal Description	Frequency, (Hz.)	
First Symmetric Mode	0.095	First Symmetric Mode	0.092	-3.2%
Second Symmetric Mode	0.102	NA	NA	NA
Third Symmetric Mode	0.123	Second Symmetric Mode	0.130	5.7%
NA	NA	Third Symmetric Mode	0.174	NA
First Asymmetric Mode	0.226	NA	NA	NA
Second Asymmetric Mode	0.243	First Asymmetric Mode	0.246	1.2%
Third Asymmetric Mode	0.259	Second Asymmetric Mode	0.271	4.6%
Fourth Symmetric Mode	0.395	Fourth Symmetric Mode	0.424	7.3%
Fifth Symmetric Mode	0.448	Fifth Symmetric Mode	0.466	4.0%
Seventh Symmetric Mode	0.505	Sixth Symmetric Mode	0.488	-3.4%
NA	NA	Seventh Symmetric Mode	0.544	NA
Ninth Symmetric Mode	0.664	Eighth Symmetric Mode	0.665	0.2%

TABLE 6 2003 Field-Measured Vertical Modes – Structure 1 versus Structure 2

Structure 1 - Field-Measured Modes		Structure 2 - Field-Measured Modes		Percent Difference
Modal Description	Frequency, (Hz.)	Modal Description	Frequency, (Hz.)	
NA	NA	First Asymmetric Mode	0.070	NA
First Symmetric Mode	0.114	NA	NA	NA
Second Symmetric Mode	0.121	NA	NA	NA
Third Symmetric Mode	0.137	NA	NA	NA
First Asymmetric Mode	0.165	NA	NA	NA
Fourth Symmetric Mode	0.175	First Symmetric Mode	0.175	0.0%
Fifth Symmetric Mode	0.239	NA	NA	NA
Sixth Symmetric Mode	0.259	Second Symmetric Mode	0.260	0.4%
NA	NA	Third Symmetric Mode	0.267	NA
NA	NA	Fourth Symmetric Mode	0.364	NA
Second Asymmetric Mode	0.361	NA	NA	NA
Eleventh Symmetric Mode	0.540	Fifth Symmetric Mode	0.534	-1.1%
NA	NA	Second Asymmetric Mode	0.707	NA
NA	NA	Sixth Symmetric Mode	0.812	NA
NA	NA	Seventh Symmetric Mode	0.858	NA
Twelfth Symmetric Mode	0.912	Eighth Symmetric Mode	0.903	-1.0%

TABLE 7 Structure 2 Longitudinal Modes – 1997 Modeled versus 2003 Field-Measured

Computer-Generated Modes - 1997		Field-Measured Modes - 2003		Percent Difference
Modal Description	Frequency, (Hz.)	Modal Description	Frequency, (Hz.)	
First Longitudinal Mode	0.134	First Longitudinal Mode	0.071	-47.0%
Second Longitudinal Mode	0.189	Second Longitudinal Mode	0.174	-7.9%
Third Longitudinal Mode	0.257	Third Longitudinal Mode	0.260	1.2%
NA	NA	Fourth Longitudinal Mode	0.266	NA
NA	NA	Fifth Longitudinal Mode	0.362	NA
NA	NA	Sixth Longitudinal Mode	0.380	NA
NA	NA	Seventh Longitudinal Mode	0.547	NA
Fourth Longitudinal Mode	0.652	Eighth Longitudinal Mode	0.649	-0.5%
NA	NA	Ninth Longitudinal Mode	0.667	NA
Fifth Longitudinal Mode	0.793	Tenth Longitudinal Mode	0.725	-8.6%

TABLE 8 Structure 2 Transverse Modes – 1997 Modeled versus 2003 Field-Measured

Computer-Generated Modes - 1997		Field-Measured Modes - 2003		Percent Difference
Modal Description	Frequency, (Hz.)	Modal Description	Frequency, (Hz.)	
First Symmetric Mode	0.078	First Symmetric Mode	0.092	18.0%
NA	NA	Second Symmetric Mode	0.130	NA
NA	NA	Third Symmetric Mode	0.174	NA
NA	NA	First Asymmetric Mode	0.246	NA
NA	NA	Second Asymmetric Mode	0.271	NA
Second Symmetric Mode	0.290	NA	NA	NA
Third Symmetric Mode	0.333	NA	NA	NA
Fourth Symmetric Mode	0.404	Fourth Symmetric Mode	0.424	5.0%
Fifth Symmetric Mode	0.461	Fifth Symmetric Mode	0.466	1.1%
NA	NA	Sixth Symmetric Mode	0.488	NA
Sixth Symmetric Mode	0.537	Seventh Symmetric Mode	0.544	1.3%
Seventh Symmetric Mode	0.588	NA	NA	NA
NA	NA	Eighth Symmetric Mode	0.665	NA
Unspecified Mode Shape	0.675	NA	NA	NA
Unspecified Mode Shape	0.721	NA	NA	NA
Unspecified Mode Shape	0.808	NA	NA	NA
Unspecified Mode Shape	0.854	NA	NA	NA
Eighth Symmetric Mode	0.933	NA	NA	NA

TABLE 9 Structure 2 Vertical Modes – 1997 Modeled versus 2003 Field-Measured

Computer-Generated Modes - 1997		Field-Measured Modes - 2003		Percent Difference
Modal Description	Frequency, (Hz.)	Modal Description	Frequency, (Hz.)	
First Asymmetric Mode	0.134	First Asymmetric Mode	0.070	-47.8%
First Symmetric Mode	0.169	First Symmetric Mode	0.175	3.6%
Second Asymmetric Mode	0.189	NA	NA	NA
Third Asymmetric Mode	0.257	NA	NA	NA
NA	NA	Second Symmetric Mode	0.260	NA
NA	NA	Third Symmetric Mode	0.267	NA
Second Symmetric Mode	0.341	Fourth Symmetric Mode	0.364	6.8%
Third Symmetric Mode	0.500	Fifth Symmetric Mode	0.534	6.8%
Fourth Asymmetric Mode	0.652	Second Asymmetric Mode	0.707	8.4%
Unspecified Mode Shape	0.793	NA	NA	NA
Fourth Symmetric Mode	0.826	Sixth Symmetric Mode	0.812	-1.7%
Fifth Symmetric Mode	0.831	Seventh Symmetric Mode	0.858	3.3%
NA	NA	Eighth Symmetric Mode	0.903	NA