# Appendix

## Testing Equipment

### Accelerometer

Table : PCB 393A03 Model Specifications

|  |  |
| --- | --- |
| Sensitivity: | (±5%) 1000 mV/g (102 mV/(m/s²)) |
| Measurement Range: | ±5 g pk (±49 m/s² pk) |
| Broadband Resolution: | 0.00001 g rms (0.0001 m/s² rms) |
| Frequency Range: | (±5%) 0.5 to 2000 Hz |
| Electrical Connector: | 2-Pin MIL-C-5015 |
| Weight: | 7.4 oz (210 gm) |

### Strain Gauge

Table : Geokon Model 4000 Specifications

|  |  |
| --- | --- |
| Measurement Range: | 3000 µε |
| Resolution: | 1.0 µε |
| Accuracy: | ±0.5% F.S. |
| Nonlinearity: | <0.5% F.S. |
| Temperature Range: | −20°C to +80°C |
| Active Gauge Length | 150 mm |

## Case Study: Phase 1 Testing

### Longitudinal Acceleration Time History

|  |  |  |
| --- | --- | --- |
| Acceleration (g) |  | Pier 2 |
|  | Pier 3 |
|  | Pier 5 |
|  | Pier 7 |
|  | Time (sec) ◼-West; ◼-East |  |

### Vertical Acceleration Time History

|  |  |  |
| --- | --- | --- |
| Acceleration (g) |  | Pier 2 |
|  | Pier 3 |
|  | Pier 5 |
|  | Pier 7 |
|  | Time (sec) |  |

### Phase 2 Testing

#### Mode shapes

## FE Model Creation

### 3D Element-based model

This model type employs

### Plate Eccentric-Beam (PEB) model

## FE Model Validation

### Phase 2

### Phase 3

|  |  |
| --- | --- |
| FE Modes | Experimental Modes |
| 2.03 Hz | 2.0 Hz |
| 2.07 Hz | 2.1 Hz |
| 2.49 Hz | 2.44 Hz |
| 2.50 Hz | 2.54 Hz |
| 2.82 Hz | 2.83 Hz |
| 3.14 Hz | 3.2 Hz |
| 3.63 Hz | 3.56 Hz |
| 3.63 Hz | 3.56 Hz |

## State-Space Model Validation

Validation of the 2-DOF state-space models was performed by comparing responses to those predicted by 2D FE models of the beams. The following lists the beam parameters as assigned in the state-space model.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Bridge/Beam Parameters | | | Vehicle/Sprung Mass Parameters | | |
| Length | 1200 | in | Mass | 100 | slinch |
| EI | 7.50E+12 | lb-in2 | Spring K | 6.32E+04 | lb/in |
| Total Mass | 460000 | lb | Damping Coefficient | 502.65 | lb-s/in |
| Length | 1200 | in |  |  |  |

The FE models were constructed with 2D Kirchhoff beam elements which are parabolically curved thin beam elements in which shear deformations are excluded. The beams were discretized with a mesh length of 6 inches. The elements were assigned the following attributes.

Table 3: FEM Beam Attributes

|  |  |  |
| --- | --- | --- |
| Moment of Inertia (I) | 1500 | in^4 |
| Cross sectional area (A) | 10 | in^2 |
| Modulus of Elasticity (E) | 5.00E+09 | psi |
| Material Density | 0.099286 | slinch/in^3 |

The sprung-mass in the FE model was assigned the same attributes as listed for the state-space model.

The profile was constructed using ISO 8608 standards whereby two parameters describe the frequency content of the profile. For these simulations a profile was constructed with a roughness coefficient (C10) of 300 and a waviness (*w*) of -2. A profile with these parameters would be categorized as average according to ISO 8608. The profile was located such that the beam began at the profile’s distance of 100 feet.

The sprung mass was assigned a velocity of 720 in/sec. Its path began 100 feet before the beam at the beginning of the profile. The state-space model evaluated each state in increments of 1 inch thus resulting in a time-step of 0.0014 sec. The FE simulations were performed with a time-step of 0.0015 sec.

### Comparison of state-space to FEM for single-span

Figure 1: Comparison of midspan displacement

Figure 2: Comparison of force at vehicle contact point

### Comparison of state-space to FEM for two-span continuous

Figure 3: Comparison of midspan (span 1) displacement

Figure 4: Comparison of force at vehicle contact point

## Construction of Artificial Profiles

## Simulation of VBI with Traffic

Table 4: Vehicles and their corresponding sprung-mass properties

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Vehicle # | Axle # | Name | Distance from rear axle (ft) | Weight (kip) | Mass (slinch) | Spring Stiffness (kip/in) | Damping Coefficient (lb-s/in) | Damping Ratio | Natural Frequency |
| 1 | 1 | HS20-32\_1 | 0 | 32 | 82.882 | 20 | 257.529 | 0.1 | 2.472 |
| 1 | HS20-32\_1 | 14 | 32 | 82.882 | 20 | 257.529 | 0.1 | 2.472 |
| 2 | HS20-8\_1 | 28 | 8 | 20.721 | 15 | 111.513 | 0.1 | 4.282 |
| 2 | 3 | HS20-32\_2 | 0 | 32 | 82.882 | 16 | 460.682 | 0.2 | 2.211 |
| 3 | HS20-32\_2 | 30 | 32 | 82.882 | 16 | 460.682 | 0.2 | 2.211 |
| 4 | HS20-8\_2 | 44 | 8 | 20.721 | 8 | 407.189 | 0.5 | 3.127 |
| 3 | 5 | HS20-32\_3 | 0 | 32 | 82.882 | 13 | 415.253 | 0.2 | 1.993 |
| 5 | HS20-32\_3 | 22 | 32 | 82.882 | 13 | 415.253 | 0.2 | 1.993 |
| 6 | HS20-8\_3 | 36 | 8 | 20.721 | 10 | 455.251 | 0.5 | 3.496 |
| 4 | 7 | tst-tand | 0 | 17 | 44.031 | 15 | 162.557 | 0.1 | 2.937 |
| 7 | tst-tand | 6 | 17 | 44.031 | 15 | 162.557 | 0.1 | 2.937 |
| 8 | tst-drive | 29 | 17 | 44.031 | 15 | 162.557 | 0.1 | 2.937 |
| 8 | tst-drive | 35 | 17 | 44.031 | 15 | 162.557 | 0.1 | 2.937 |
| 9 | tst-front | 51 | 12 | 31.081 | 2.2 | 261.522 | 0.5 | 1.339 |
| 5 | 10 | dump-rear | 0 | 25 | 64.752 | 12 | 176.318 | 0.1 | 2.166 |
| 10 | dump-rear | 5 | 25 | 64.752 | 12 | 176.318 | 0.1 | 2.166 |
| 11 | dump-front | 20 | 20 | 51.801 | 12 | 315.407 | 0.2 | 2.422 |
| 6 | 12 | car1 | 0 | 1.5 | 3.885 | 0.2 | 27.878 | 0.5 | 1.142 |
| 12 | car1 | 8 | 1.5 | 3.885 | 0.2 | 27.878 | 0.5 | 1.142 |
| 7 | 13 | car2 | 0 | 2 | 5.180 | 0.4 | 45.525 | 0.5 | 1.398 |
| 13 | car2 | 10 | 2 | 5.180 | 0.4 | 45.525 | 0.5 | 1.398 |
| 8 | 14 | car3 | 0 | 3 | 7.770 | 2 | 124.676 | 0.5 | 2.553 |
| 14 | car3 | 14 | 3 | 7.770 | 2 | 124.676 | 0.5 | 2.553 |

Table 5: Traffic Pattern Parameters

|  |  |  |  |
| --- | --- | --- | --- |
|  | Num. of Vehicles | Min. Spacing (ft.) | Max. Spacing (ft.) |
| 1 | 36 | 20 | 100 |
| 2 | 36 | 40 | 200 |
| 3 | 36 | 60 | 300 |
| 4 | 36 | 80 | 400 |
| 5 | 36 | 100 | 500 |
| 6 | 36 | 280 | 1400 |

Table 6: Spring-mass configuration for traffic patterns

|  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| 1 | | 2 | | 3 | | 4 | | 5 | | 6 | |
| Location (in) | Axle # | Location (in) | Axle # | Location (in) | Axle # | Location (in) | Axle # | Location (in) | Axle # | Location (in) | Axle # |
| 0 | 6 | 0 | 2 | 0 | 9 | 0 | 9 | 0 | 4 | 0 | 4 |
| -168 | 5 | -168 | 1 | -192 | 8 | -192 | 8 | -168 | 3 | -168 | 3 |
| -432 | 5 | -336 | 1 | -264 | 8 | -264 | 8 | -528 | 3 | -528 | 3 |
| -1260 | 2 | -2028 | 6 | -540 | 7 | -540 | 7 | -2676 | 2 | -17220 | 12 |
| -1428 | 1 | -2196 | 5 | -612 | 7 | -612 | 7 | -2844 | 1 | -17316 | 12 |
| -1596 | 1 | -2460 | 5 | -3096 | 2 | -2496 | 14 | -3012 | 1 | -21672 | 12 |
| -1860 | 6 | -4260 | 14 | -3264 | 1 | -2664 | 14 | -6816 | 9 | -21768 | 12 |
| -2028 | 5 | -4428 | 14 | -3432 | 1 | -4584 | 11 | -7008 | 8 | -35880 | 9 |
| -2292 | 5 | -5568 | 12 | -5208 | 6 | -4764 | 10 | -7080 | 8 | -36072 | 8 |
| -2880 | 9 | -5664 | 12 | -5376 | 5 | -4824 | 10 | -7356 | 7 | -36144 | 8 |
| -3072 | 8 | -6828 | 2 | -5640 | 5 | -9192 | 12 | -7428 | 7 | -36420 | 7 |
| -3144 | 8 | -6996 | 1 | -7752 | 13 | -9288 | 12 | -10320 | 13 | -36492 | 7 |
| -3420 | 7 | -7164 | 1 | -7872 | 13 | -11100 | 6 | -10440 | 13 | -43068 | 14 |
| -3492 | 7 | -8772 | 13 | -9396 | 6 | -11268 | 5 | -12408 | 14 | -43236 | 14 |
| -4632 | 12 | -8892 | 13 | -9564 | 5 | -11532 | 5 | -12576 | 14 | -47508 | 2 |
| -4728 | 12 | -10860 | 12 | -9828 | 5 | -13092 | 13 | -16788 | 4 | -47676 | 1 |
| -5640 | 14 | -10956 | 12 | -11520 | 11 | -13212 | 13 | -16956 | 3 | -47844 | 1 |
| -5808 | 14 | -11760 | 6 | -11700 | 10 | -15780 | 12 | -17316 | 3 | -56724 | 14 |
| -6960 | 12 | -11928 | 5 | -11760 | 10 | -15876 | 12 | -22140 | 9 | -56892 | 14 |
| -7056 | 12 | -12192 | 5 | -12672 | 11 | -18036 | 14 | -22332 | 8 | -61128 | 6 |
| -8064 | 11 | -14148 | 4 | -12852 | 10 | -18204 | 14 | -22404 | 8 | -61296 | 5 |
| -8244 | 10 | -14316 | 3 | -12912 | 10 | -21132 | 4 | -22680 | 7 | -61560 | 5 |
| -8304 | 10 | -14676 | 3 | -15180 | 4 | -21300 | 3 | -22752 | 7 | -75024 | 11 |
| -8904 | 12 | -16632 | 2 | -15348 | 3 | -21660 | 3 | -26928 | 9 | -75204 | 10 |
| -9000 | 12 | -16800 | 1 | -15708 | 3 | -25524 | 13 | -27120 | 8 | -75264 | 10 |
| -10092 | 11 | -16968 | 1 | -17316 | 12 | -25644 | 13 | -27192 | 8 | -84300 | 11 |
| -10272 | 10 | -18336 | 4 | -17412 | 12 | -28644 | 14 | -27468 | 7 | -84480 | 10 |
| -10332 | 10 | -18504 | 3 | -19740 | 11 | -28812 | 14 | -27540 | 7 | -84540 | 10 |
| -10680 | 9 | -18864 | 3 | -19920 | 10 | -30504 | 9 | -29844 | 2 | -98004 | 12 |
| -10872 | 8 | -19824 | 14 | -19980 | 10 | -30696 | 8 | -30012 | 1 | -98100 | 12 |
| -10944 | 8 | -19992 | 14 | -23040 | 13 | -30768 | 8 | -30180 | 1 | -102528 | 2 |
| -11220 | 7 | -21540 | 2 | -23160 | 13 | -31044 | 7 | -33036 | 6 | -102696 | 1 |
| -11292 | 7 | -21708 | 1 | -24312 | 12 | -31116 | 7 | -33204 | 5 | -102864 | 1 |
| -12204 | 6 | -21876 | 1 | -24408 | 12 | -35664 | 11 | -33468 | 5 | -109392 | 14 |
| -12372 | 5 | -23760 | 6 | -25596 | 11 | -35844 | 10 | -39420 | 6 | -109560 | 14 |
| -12636 | 5 | -23928 | 5 | -25776 | 10 | -35904 | 10 | -39588 | 5 | -122256 | 2 |
| -13584 | 12 | -24192 | 5 | -25836 | 10 | -37584 | 12 | -39852 | 5 | -122424 | 1 |
| -13680 | 12 | -25716 | 9 | -28620 | 6 | -37680 | 12 | -44664 | 13 | -122592 | 1 |
| -14460 | 14 | -25908 | 8 | -28788 | 5 | -39312 | 14 | -44784 | 13 | -139116 | 13 |
| -14628 | 14 | -25980 | 8 | -29052 | 5 | -39480 | 14 | -46188 | 6 | -139236 | 13 |
| -15456 | 13 | -26256 | 7 | -30588 | 6 | -43752 | 12 | -46356 | 5 | -146268 | 12 |
| -15576 | 13 | -26328 | 7 | -30756 | 5 | -43848 | 12 | -46620 | 5 | -146364 | 12 |
| -16368 | 13 | -27276 | 11 | -31020 | 5 | -45696 | 13 | -51708 | 6 | -156360 | 2 |
| -16488 | 13 | -27456 | 10 | -33636 | 11 | -45816 | 13 | -51876 | 5 | -156528 | 1 |
| -17280 | 9 | -27516 | 10 | -33816 | 10 | -49164 | 9 | -52140 | 5 | -156696 | 1 |
| -17472 | 8 | -28356 | 12 | -33876 | 10 | -49356 | 8 | -54936 | 9 | -162732 | 2 |
| -17544 | 8 | -28452 | 12 | -35028 | 13 | -49428 | 8 | -55128 | 8 | -162900 | 1 |
| -17820 | 7 | -30072 | 11 | -35148 | 13 | -49704 | 7 | -55200 | 8 | -163068 | 1 |
| -17892 | 7 | -30252 | 10 | -36588 | 13 | -49776 | 7 | -55476 | 7 | -171156 | 6 |
| -18348 | 13 | -30312 | 10 | -36708 | 13 | -50904 | 4 | -55548 | 7 | -171324 | 5 |
| -18468 | 13 | -32340 | 12 | -39492 | 12 | -51072 | 3 | -57480 | 11 | -171588 | 5 |
| -19236 | 11 | -32436 | 12 | -39588 | 12 | -51432 | 3 | -57660 | 10 | -175704 | 4 |
| -19416 | 10 | -34416 | 4 | -41280 | 11 | -55764 | 11 | -57720 | 10 | -175872 | 3 |
| -19476 | 10 | -34584 | 3 | -41460 | 10 | -55944 | 10 | -61608 | 12 | -176232 | 3 |
| -20052 | 2 | -34944 | 3 | -41520 | 10 | -56004 | 10 | -61704 | 12 | -183612 | 14 |
| -20220 | 1 | -37224 | 13 | -42312 | 4 | -57408 | 12 | -63660 | 2 | -183780 | 14 |
| -20388 | 1 | -37344 | 13 | -42480 | 3 | -57504 | 12 | -63828 | 1 | -198480 | 4 |
| -21372 | 11 | -38256 | 12 | -42840 | 3 | -61176 | 2 | -63996 | 1 | -198648 | 3 |
| -21552 | 10 | -38352 | 12 | -45336 | 6 | -61344 | 1 | -66264 | 9 | -199008 | 3 |
| -21612 | 10 | -39456 | 14 | -45504 | 5 | -61512 | 1 | -66456 | 8 | -213192 | 4 |
| -22716 | 12 | -39624 | 14 | -45768 | 5 | -63360 | 2 | -66528 | 8 | -213360 | 3 |
| -22812 | 12 | -41688 | 11 | -47256 | 4 | -63528 | 1 | -66804 | 7 | -213720 | 3 |
| -23244 | 12 | -41868 | 10 | -47424 | 3 | -63696 | 1 | -66876 | 7 | -225048 | 14 |
| -23340 | 12 | -41928 | 10 | -47784 | 3 | -66756 | 9 | -72240 | 2 | -225216 | 14 |
| -24504 | 11 | -44004 | 6 | -50268 | 13 | -66948 | 8 | -72408 | 1 | -239328 | 12 |
| -24684 | 10 | -44172 | 5 | -50388 | 13 | -67020 | 8 | -72576 | 1 | -239424 | 12 |
| -24744 | 10 | -44436 | 5 | -53832 | 6 | -67296 | 7 | -77412 | 12 | -243732 | 9 |
| -25068 | 11 | -46416 | 12 | -54000 | 5 | -67368 | 7 | -77508 | 12 | -243924 | 8 |
| -25248 | 10 | -46512 | 12 | -54264 | 5 | -71616 | 2 | -81696 | 6 | -243996 | 8 |
| -25308 | 10 | -47664 | 12 | -56676 | 4 | -71784 | 1 | -81864 | 5 | -244272 | 7 |
| -26232 | 14 | -47760 | 12 | -56844 | 3 | -71952 | 1 | -82128 | 5 | -244344 | 7 |
| -26400 | 14 | -48684 | 12 | -57204 | 3 | -73116 | 4 | -85752 | 11 | -252432 | 9 |
| -27096 | 12 | -48780 | 12 | -60420 | 2 | -73284 | 3 | -85932 | 10 | -252624 | 8 |
| -27192 | 12 | -50520 | 12 | -60588 | 1 | -73644 | 3 | -85992 | 10 | -252696 | 8 |
| -27696 | 9 | -50616 | 12 | -60756 | 1 | -75912 | 9 | -91596 | 13 | -252972 | 7 |
| -27888 | 8 | -51444 | 12 | -61584 | 11 | -76104 | 8 | -91716 | 13 | -253044 | 7 |
| -27960 | 8 | -51540 | 12 | -61764 | 10 | -76176 | 8 | -95220 | 6 | -261276 | 2 |
| -28236 | 7 | -52248 | 14 | -61824 | 10 | -76452 | 7 | -95388 | 5 | -261444 | 1 |
| -28308 | 7 | -52416 | 14 | -63888 | 6 | -76524 | 7 | -95652 | 5 | -261612 | 1 |
| -28896 | 6 | -53988 | 12 | -64056 | 5 | -79344 | 6 | -98028 | 4 | -266820 | 14 |
| -29064 | 5 | -54084 | 12 | -64320 | 5 | -79512 | 5 | -98196 | 3 | -266988 | 14 |
| -29328 | 5 | -55884 | 13 | -66372 | 2 | -79776 | 5 | -98556 | 3 | -278844 | 2 |
| -30132 | 6 | -56004 | 13 | -66540 | 1 | -81156 | 9 | -102936 | 4 | -279012 | 1 |
| -30300 | 5 | -56856 | 12 | -66708 | 1 | -81348 | 8 | -103104 | 3 | -279180 | 1 |
| -30564 | 5 | -56952 | 12 | -68292 | 9 | -81420 | 8 | -103464 | 3 | -291204 | 12 |
| -30804 | 2 | -59124 | 9 | -68484 | 8 | -81696 | 7 | -109104 | 11 | -291300 | 12 |
| -30972 | 1 | -59316 | 8 | -68556 | 8 | -81768 | 7 | -109284 | 10 | -305184 | 6 |
| -31140 | 1 | -59388 | 8 | -68832 | 7 | -85044 | 9 | -109344 | 10 | -305352 | 5 |
| -31776 | 2 | -59664 | 7 | -68904 | 7 | -85236 | 8 | -112152 | 14 | -305616 | 5 |
| -31944 | 1 | -59736 | 7 | -70512 | 9 | -85308 | 8 | -112320 | 14 | -319728 | 2 |
| -32112 | 1 | -60216 | 11 | -70704 | 8 | -85584 | 7 | -116232 | 6 | -319896 | 1 |
| -32712 | 6 | -60396 | 10 | -70776 | 8 | -85656 | 7 | -116400 | 5 | -320064 | 1 |
| -32880 | 5 | -60456 | 10 | -71052 | 7 | -88620 | 11 | -116664 | 5 | -336072 | 6 |
| -33144 | 5 |  |  | -71124 | 7 | -88800 | 10 | -121332 | 11 | -336240 | 5 |
| -34056 | 6 |  |  | -72708 | 14 | -88860 | 10 | -121512 | 10 | -336504 | 5 |
| -34224 | 5 |  |  | -72876 | 14 | -90132 | 9 | -121572 | 10 | -348972 | 6 |
| -34488 | 5 |  |  | -74076 | 6 | -90324 | 8 | -125028 | 12 | -349140 | 5 |
| -35616 | 6 |  |  | -74244 | 5 | -90396 | 8 | -125124 | 12 | -349404 | 5 |
| -35784 | 5 |  |  | -74508 | 5 | -90672 | 7 | -130368 | 13 | -352764 | 11 |
| -36048 | 5 |  |  | -77904 | 6 | -90744 | 7 | -130488 | 13 | -352944 | 10 |
| -36288 | 11 |  |  | -78072 | 5 | -94620 | 12 | -135372 | 2 | -353004 | 10 |
| -36468 | 10 |  |  | -78336 | 5 | -94716 | 12 | -135540 | 1 |  |  |
| -36528 | 10 |  |  | -79056 | 11 | -98316 | 11 | -135708 | 1 |  |  |
|  |  |  |  | -79236 | 10 | -98496 | 10 | -137640 | 11 |  |  |
|  |  |  |  | -79296 | 10 | -98556 | 10 | -137820 | 10 |  |  |
|  |  |  |  |  |  | -103164 | 11 | -137880 | 10 |  |  |
|  |  |  |  |  |  | -103344 | 10 | -139080 | 11 |  |  |
|  |  |  |  |  |  | -103404 | 10 | -139260 | 10 |  |  |
|  |  |  |  |  |  | -104364 | 11 | -139320 | 10 |  |  |
|  |  |  |  |  |  | -104544 | 10 |  |  |  |  |
|  |  |  |  |  |  | -104604 | 10 |  |  |  |  |

Table 7: Simulation Decisions

|  |  |  |
| --- | --- | --- |
| Decision | Selection | Units |
| Number of modes to solve for/include | 15 |  |
| Incremental distance along load-path | 6 | inches |
| Time integration scheme | Hilber Hughes Taylor (HHT) |  |
| Profile interpolation method | Linear |  |
| Structural damping | 1% |  |
| Traffic speed | 960, 5 | in/sec |
| Solution time-step | 0.0015, 0.5 | sec |