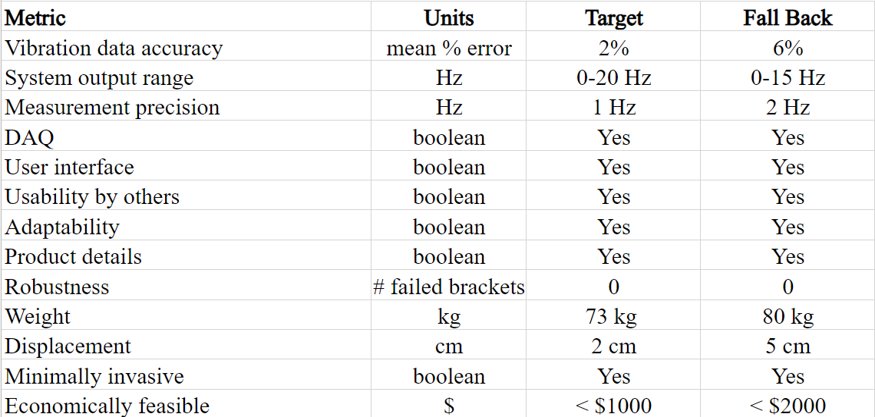
**Test Plan Report**

1. Introduction

The Downey1 group conducted engineering tests on the bridge shaker to evaluate its performance with respect to the target and fallback specifications, listed in Table 1. The team consulted the list of priority needs to decide the target and fallback specifications on which to perform engineering testing. It was decided that the vibration data accuracy, system output range, instrument resolution, robustness, weight, and displacement should be assessed. These were chosen because they align with the top seven needs and have specific ranges that are key to the project application. The team decided not to test any of the boolean specifications as they could not be verified through empirical engineering testing. The tests and their results are outlined in this document.

Table 1. Target and Fallback Specifications



2. Test Methods

As previously mentioned, the parameters that will be examined in this report are vibration data accuracy, system output range, instrument resolution, robustness, weight, and displacement. There are six simple tests that need to be performed to ensure that the shaker is in good working order. The first three tests are concerned with the functional performance of the shaker as a tool for structural excitation. The first of these is to ensure that the shaker is producing accurate vibrations to excite the modal frequencies of whatever bridge or structure it has been placed on. The methodology for this test has been laid out below.

1. Test vibration data
   1. Parameter: Mean percent error
   2. Target value, Fallback value: 2%, 6%
   3. Testing Procedure: To verify that the shaker is functioning correctly to test vibration data, one PCB Piezotronics ceramic shear accelerometer and the shaker will be placed onto a pedestrian bridge, and another PCB Piezotronics ceramic shear accelerometer will be placed on the shaker. The accelerometers will report data through an NI DAQ system with an IEPE accelerometer module to LabVIEW. The shaker will be turned on, and the corresponding vibration data will be collected by the accelerometers as time domain amplitude data and will be put into the frequency domain using a Fast Fourier Transform (FFT). This test will only be performed once. The verification test will be considered successful if the accelerometers detect peaks in vibration within 2% of the specified frequency of the shaker.

The second test that must be conducted is to ensure that the shaker can operate at a range of frequencies to find the resonance frequencies of the structure. Testing this range from 0-20 Hz should be done prior to product handoff. The procedure and explanation follow.

1. Operate at different frequencies
   1. Parameter: Frequency (Hz)
   2. Target value, Fallback value: 0-20 Hz, 0-15 Hz
   3. Testing Procedure: The shaker’s output range should conform to the specifications table, which requires it to operate between 0-20 Hz. This range was chosen to ensure that the shaker has the capacity to stimulate lower frequencies that are inherent to a pedestrian bridge, particularly one that is comprised of concrete. The shaker and a PCB Piezotronics ceramic shears accelerometer will be placed onto a pedestrian bridge. A second PCB Piezotronics ceramic shears accelerometer will be placed directly onto the shaker. Once the shaker is activated, data will be read into LabVIEW from both the accelerometer on the bridge as well as the accelerometer on the shaker through a DAQ system equipped with an IEPE accelerometer module. The team will assess the functionality of the shaker once at different frequencies of 5 Hz, 10 Hz, 15 Hz, and 20 Hz, and the accelerometers will be utilized to process the resulting time domain data with an FFT. The test will be considered successful if the accelerometers read the specified peaks that are output by the shaker.

Thirdly, the shaker’s resolution must be explored. The team designed the shaker so that the shaker could operate closely to the desired frequency. The target specification was 1 Hz, but the group has experienced better control than 1 Hz. For this test, the procedure for validating high resolution is explained.

1. Resolution of at least 1 Hz
   1. Parameter: Frequency (Hz)
   2. Target value, Fallback value: ±1 Hz, ±2 Hz
   3. Testing Procedure: To test the resolution, the shaker and a PCB Piezotronics ceramic shear accelerometer will be placed on a pedestrian bridge as well as a second accelerometer of the same type on the shaker. As with previous tests, LabVIEW and a DAQ system including an IEPE module will be used to read the data from the accelerometers. The shaker will be set to 10 Hz output and allowed to stabilize at this frequency. The accelerometers will be used to verify that the shaker is at 10 Hz using an FFT on the time domain data. Then, the shaker will be set to 11 Hz and the accelerometer will be used again to verify the frequency. The test will only need to be run once as the shaker’s functionality is relatively static. If the measured frequencies match the set frequencies with a difference of 1 Hz, then the test will be deemed successful.

The next three tests focus more on the physical structure of the shaker. The first of these centers around the overall weight of the shaker. This test is very simple and requires only a scale. The shaker was designed to be easily carried by two people and then have additional weight in the form of sandbags added after the shaker is in place on the bridge. This test should only be conducted once the shaker has been assembled and then after additions or subtractions from the product have been made.

1. Portable
2. Parameter: Weight (kg)
3. Target value, Fallback value: 73 kg, 80 kg
4. Testing procedure: The weight of the shaker must be between 73 and 80 kg, according to the target and fallback specifications table. These specifications are to allow two people to comfortably transport the shaker. The weight of the shaker will be tested using an industrial scale located in the materials test lab. The shaker will be set on the scale while turned off and the data recorded manually by reading the value, no data processing needed. The shaker will be weighed while turned off because that reflects the state in which it will be transported.

This next test should be done before, during, and after any test is performed. The shaker will inherently create forces that will strain or loosen the connections holding it together. For this reason, it is vital to the safety of the operators and the device itself that the procedures are followed well. Failures in joints could result in negative consequences to the people, shaker, or structure in the surrounding area. The procedures for checking the joints are as follows.

1. Robust
   1. Parameter: # of failed brackets
   2. Target value, Fallback value: 0 brackets, 0 brackets
   3. Testing Procedure: During testing, each of the joints will be inspected to ensure system stability. The frame is what holds everything together, and without it, the entire system could be a potential hazard. The first test will be conducted when the motor is at low speed at 5 Hz, medium speed at 10 Hz, and high speed at 15 Hz. After each test, all joints of the shaker frame and moving parts from the drive train will be inspected, as well as all fasteners to ensure they do not come loose during operation. The target and fallback specification are the same, as there is no number of failed brackets that are acceptable.

Lastly, to ensure that the shaker is transferring as much energy as possible to the bridge or structure, a test must be performed after the experimental testing is complete. If the shaker begins ‘walking’ (as described below), the shaker will be less efficient while also making the data collected far less useful. This is another very simple but very important test to the success of the shaker.

1. Good contact to bridge
   1. Parameter: Displacement in cm
   2. Target value, Fallback value: 2 cm, 5 cm
   3. Testing Procedure: The initial and final position of the shaker after operation must have a difference no greater than 2 cm. The movement of the shaker is considered “walking. “Walking” in this sense is the movement of the shaker in the ‘X’, ‘Y’, or ‘Z’ direction. To assess the ‘X’ and ‘Y’ directions, the team will mark the initial position of the shaker on the bridge and then run a test. After the test is completed, the team can observe the total movement of the shaker over the test with a ruler or calipers. If there is significant ‘walking’ then more weight will be added to the extended legs. To observe the movement in the ‘Z’ direction (vertical in this case), the team will physically observe the shaker and ensure that it is staying down on the bridge. This test does not require data processing.

3. Analysis

After completing Tests I-III, an FFT was performed on the raw acceleration data read from the accelerometers. For each test, the sampling frequency of 2460 samples/second over a 3 second test yields 7380 raw data points. Because of this, raw data is not supplied in tabular form, but rather visually displayed in graphical form as time-domain data, shown in figure 1. In the context of vibration testing, an FFT is used to analyze and transform time-domain data, as seen in figure 1, into frequency-domain components, as seen in figures 2-6. This transformation allows the identification and visualization of the different frequencies of the structure the accelerometers are placed on. The equation for the FFT is:

Chart

Description automatically generated

Figure 1: Time-domain data from 10 Hz frequency test.

The time-domain data presented above reveals a large contrast in the levels of excitation measured by the green and blue accelerometers. This can be attributed to the positioning of the accelerometers, with the green one placed directly on the shaker and the blue one placed on the bridge. Owing to its proximity to the vibration source, the green accelerometer registers a higher level of acceleration. In contrast, the blue accelerometer measures a lower acceleration as it accounts for the response of the bridge to the induced vibration.

Chart, histogram

Description automatically generated

Figure 2: Frequency-domain data from 5 Hz test.

Chart, histogram

Description automatically generated

Figure 3: Frequency-domain data from 10 Hz test.

Chart, histogram

Description automatically generated

Figure 4: Frequency-domain data from 11 Hz test.

Graphical user interface, chart, histogram

Description automatically generated

Figure 5: Frequency-domain data from 15 Hz test.

Chart

Description automatically generated

Figure 6: Frequency-domain data from 20 Hz test.

The results presented above demonstrate highly promising outcomes for vibration testing. The tests revealed a remarkably low mean percent error of 5.1923% for the 5, 10, 15, and 20 Hz tests. Particularly impressive were the test results at 10 and 11 Hz, exhibiting percentage errors of 0.228% and 0.543%, respectively. These outcomes are especially encouraging since the predicted first modal frequency of the bridge structure was estimated to occur around 10-11 Hz. As such, these frequencies were anticipated to produce more pronounced vibrations, leading to reduced error in the accelerometer data. With this information, the tests ran were considered acceptable for the final product.

Tests IV-VI were recorded as individual values and will be addressed individually in this report. In Test IV for portability, the recorded weight of the shaker was 50 kg, which falls far below the target value. During testing, the shaker was also transported easily with two people, satisfying the portability specification.

Test V for robustness showed that after testing in the higher frequencies, specifically at 20 Hz, multiple brackets were broken by the force of operation. After inspection, it was found that the shaft bearing had deformed from the force of operation, which resulted in the shaft oscillating vertically and inducing unexpected stress on the frame. It was theorized that this stress was what caused the brackets to fail, and the shaft bearings were changed to sturdier zinc die-cast bearings. These bearings did not deform during subsequent testing and the shaft oscillation has not been an issue, reducing the broken bracket count to zero even at high frequencies and satisfying the robustness specification.

Test VI for displacement resulted in a 19 cm displacement in the Y direction when the shaker was operated at 20 Hz, far above the 5 cm fallback value. This issue was due to too little weight holding the shaker down during operation, resulting in poor contact to the bridge. It has been addressed by adding additional sandbags on the shaker periphery, which has eliminated the displacement issue and satisfied the testing requirements. In future iterations, supports will be added to place sandbags on top of the shaker directly above the linear weight to optimize energy transfer and reduce required supplemental weight.

4. Conclusions/Recommendations

Table 2. Engineering test results compared to target and fallback specifications.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Parameter** | **Target value** | **Fallback value** | **Measured performance** | **Satisfactory? (Y/N)** |
| Vibration Data Accuracy | 2% | 6% | 0.228% | Y |
| System Output Range | 0-20 Hz | 0-15 Hz | 0-15 Hz | Y |
| Measurement Precision | 1 Hz | 2 Hz | 1.037 Hz | Y |
| Portability | 73 kg | 80 kg | 50 kg | Y |
| Robust | 0 Failed Brackets | 0 Failed Brackets | 1+ Failed Brackets | N |
| Displacement | 2 cm | 5 cm | 19 cm | N |

As shown in Table 2, the tests for vibration data accuracy, system output range, instrument resolution, robustness, weight, and displacement have been performed and largely satisfy the target/fallback specifications. The Boolean parameters were not tested because they corresponded to lower priority needs and were not suited for engineering performance tests. The vibration data accuracy tests ensured that the data collected lacked significant error, with a measured performance of 0.288% that satisfies the target value. The system output range test displayed the viable frequency range, which is shown to be 0-15 Hz and within the fallback specification. The measurement precision test was performed to ensure the frequency of the shaker had a resolution of 1-2 Hz, which satisfied the fallback value at 1.037 Hz. The portability of the shaker was tested based on the shaker’s weight, which should be easy to carry for two people. The total weight of the shaker was measured to be 50 kg, very far below the target specification. The robustness of the shaker was also quantified by the number of brackets broken during operation. During testing, the shaker broke several 3D printed brackets at high frequencies. Optimally, the shaker will not break any brackets, and this problem was solved by switching out the shaft bearings and opting for metal brackets. The displacement of the shaker was measured to assess unwanted movement while shaking. During testing, it moved 19 cm, and additional weight was added to address the issue and satisfy the displacement specification. At this point, the product is not yet satisfactory. While the 3D printed brackets have been replaced with much sturdier metal brackets that have not failed, the distance of the shaker traveling during operation is being solved by adding a design that allows sandbags to sit on top of the frame, better securing it to the bridge. Moving forward, the team will continue to experiment with supplemental weight to decrease the shaker’s displacement. Additionally, the team is increasing the product safety by adding expanded steel on the sides to prevent injury.