

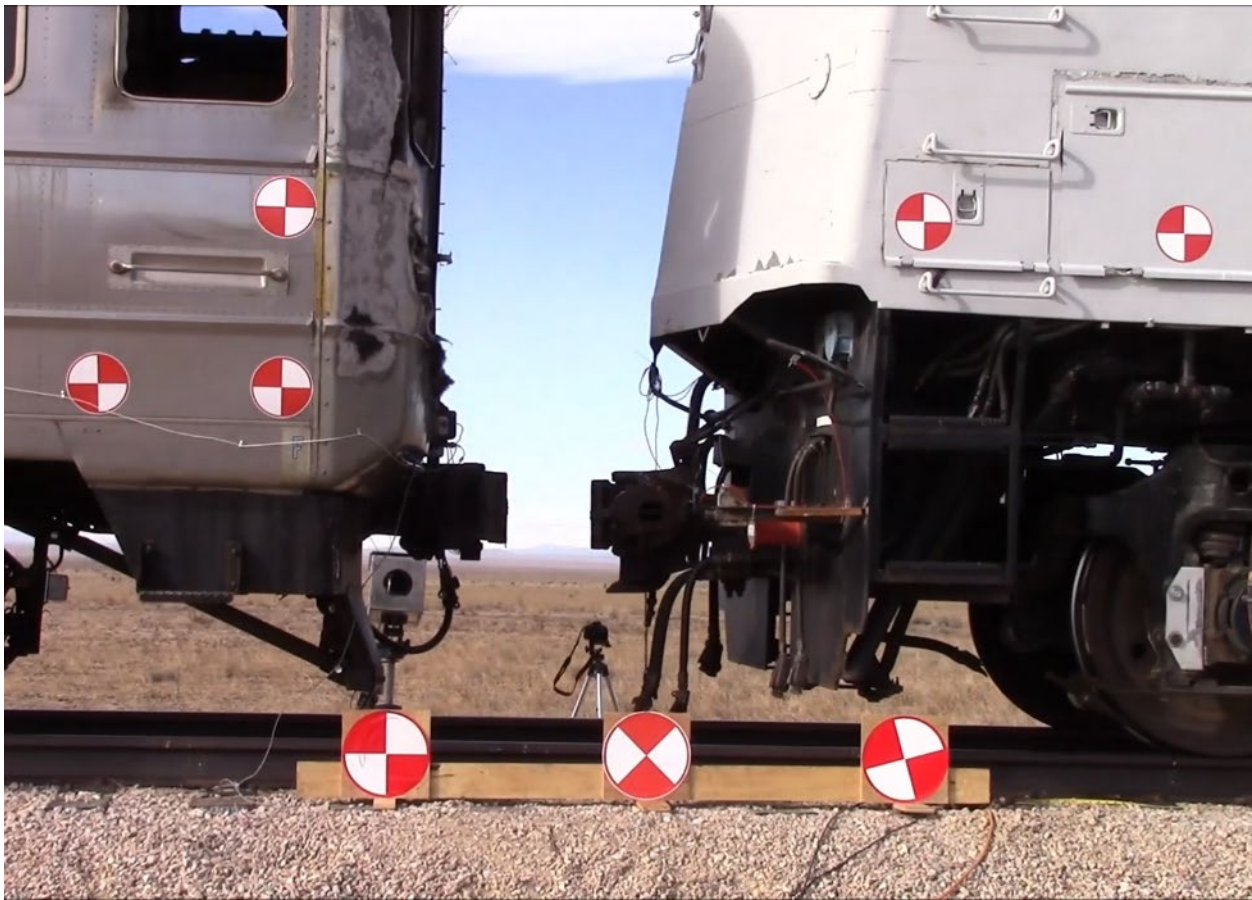


U.S. Department of
Transportation

**Federal Railroad
Administration**

Conventional Coupling Test Between Coach Car and Passenger Locomotive

Office of Research,
Development
and Technology
Washington, DC 20590



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13. ABSTRACT The Federal Railroad Administration (FRA) sponsored Transportation Technology Center, Inc. (TTCI) in conducting impact tests between a Budd M1 Car and a F40 locomotive to evaluate the performance of both vehicles under dynamic conditions. This set of impact tests were performed on November 18 and 19, 2015, at the Transportation Technology Center (TTC) in Pueblo, CO. The M1 car was impacted by the locomotive at 1.89, 3.86, 5.67, 7.89, 9.95, and 11.86 mph. The most substantial damage that occurred during the tests was inflicted upon the M1 car, with the F40 locomotive sustaining no noticeable damage. The most significant damage to the M1 was the buckling and cracking of the side sills, but the draft pocket and draft gear did show deformation after these tests.				
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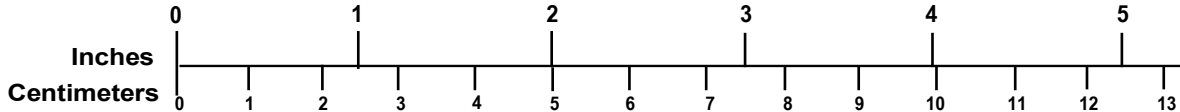
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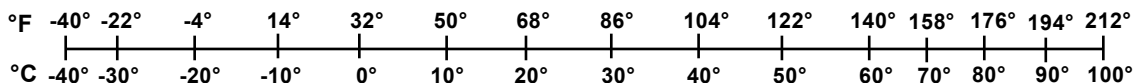
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<p>LENGTH (APPROXIMATE)</p> <p>1 inch (in) = 2.5 centimeters (cm)</p> <p>1 foot (ft) = 30 centimeters (cm)</p> <p>1 yard (yd) = 0.9 meter (m)</p> <p>1 mile (mi) = 1.6 kilometers (km)</p>	<p>LENGTH (APPROXIMATE)</p> <p>1 millimeter (mm) = 0.04 inch (in)</p> <p>1 centimeter (cm) = 0.4 inch (in)</p> <p>1 meter (m) = 3.3 feet (ft)</p> <p>1 meter (m) = 1.1 yards (yd)</p> <p>1 kilometer (km) = 0.6 mile (mi)</p>
<p>AREA (APPROXIMATE)</p> <p>1 square inch (sq in, in²) = 6.5 square centimeters (cm²)</p> <p>1 square foot (sq ft, ft²) = 0.09 square meter (m²)</p> <p>1 square yard (sq yd, yd²) = 0.8 square meter (m²)</p> <p>1 square mile (sq mi, mi²) = 2.6 square kilometers (km²)</p> <p>1 acre = 0.4 hectare (he) = 4,000 square meters (m²)</p>	<p>AREA (APPROXIMATE)</p> <p>1 square centimeter (cm²) = 0.16 square inch (sq in, in²)</p> <p>1 square meter (m²) = 1.2 square yards (sq yd, yd²)</p> <p>1 square kilometer (km²) = 0.4 square mile (sq mi, mi²)</p> <p>10,000 square meters (m²) = 1 hectare (ha) = 2.5 acres</p>
<p>MASS - WEIGHT (APPROXIMATE)</p> <p>1 ounce (oz) = 28 grams (gm)</p> <p>1 pound (lb) = 0.45 kilogram (kg)</p> <p>1 short ton = 2,000 pounds (lb) = 0.9 tonne (t)</p>	<p>MASS - WEIGHT (APPROXIMATE)</p> <p>1 gram (gm) = 0.036 ounce (oz)</p> <p>1 kilogram (kg) = 2.2 pounds (lb)</p> <p>1 tonne (t) = 1,000 kilograms (kg) = 1.1 short tons</p>
<p>VOLUME (APPROXIMATE)</p> <p>1 teaspoon (tsp) = 5 milliliters (ml)</p> <p>1 tablespoon (tbsp) = 15 milliliters (ml)</p> <p>1 fluid ounce (fl oz) = 30 milliliters (ml)</p> <p>1 cup (c) = 0.24 liter (l)</p> <p>1 pint (pt) = 0.47 liter (l)</p> <p>1 quart (qt) = 0.96 liter (l)</p> <p>1 gallon (gal) = 3.8 liters (l)</p> <p>1 cubic foot (cu ft, ft³) = 0.03 cubic meter (m³)</p> <p>1 cubic yard (cu yd, yd³) = 0.76 cubic meter (m³)</p>	<p>VOLUME (APPROXIMATE)</p> <p>1 milliliter (ml) = 0.03 fluid ounce (fl oz)</p> <p>1 liter (l) = 2.1 pints (pt)</p> <p>1 liter (l) = 1.06 quarts (qt)</p> <p>1 liter (l) = 0.26 gallon (gal)</p> <p>1 cubic meter (m³) = 36 cubic feet (cu ft, ft³)</p> <p>1 cubic meter (m³) = 1.3 cubic yards (cu yd, yd³)</p>
<p>TEMPERATURE (EXACT)</p> <p>$[(x-32)(5/9)] \text{ } \square \text{ F} = y \text{ } \square \text{ C}$</p>	<p>TEMPERATURE (EXACT)</p> <p>$[(9/5) y + 32] \text{ } \square \text{ } ^\circ \text{C} = x \text{ } \square \text{ } ^\circ \text{F}$</p>

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Executive Summary

This report documents a set of coupler impact tests between a conventional passenger car and a passenger locomotive. These tests were designed to establish a baseline maximum nondestructive coupling speed, which will be used in future testing on a passenger locomotive equipped with a crash energy management (CEM) system.

The Federal Railroad Administration (FRA) sponsored Transportation Technology Center, Inc. (TTCI) in conducting the impact tests between a Budd M1 passenger car and an F40 locomotive, and evaluated the performance of both vehicles under dynamic conditions. These impact tests were performed on November 18 and 19, 2015, at the Transportation Technology Center (TTC) in Pueblo, CO.

In six impact tests, the M1 car was impacted by the locomotive at 1.89, 3.86, 5.67, 7.89, 9.95, and 11.86 mph, respectively. The car and locomotive failed to couple during the 9.95 mph and 11.86 mph impacts, but coupled successfully in all other test runs. The M1 car sustained substantial damage during the tests, but the F40 locomotive sustained no noticeable damage. The M1 car sustained the most damage during the 9.95 mph and 11.86 mph test runs. While the most significant damage on the M1 was the buckling and cracking of the side sills, the draft pocket and draft gear on the M1 car showed deformation after these tests.

1. Introduction

1.1 Background

The Federal Railroad Administration's (FRA) Office of Research, Development and Technology, and the Volpe National Transportation Systems Center are continually evaluating new technologies that increase the safety of passengers and operators in rail equipment. Since override prevention is important in train-to-train collisions when one of the vehicles is a locomotive, and crash energy management (CEM) technologies have been successful in passenger trains, FRA has been evaluating the effectiveness of components integrated into the end structure of a locomotive that are specifically designed to mitigate the effects of a collision and, in particular, prevent the override of one of the lead vehicles onto the other.

This research program will eventually integrate two CEM components (i.e., a deformable anti-climber and a push-back coupler) onto a locomotive in order to demonstrate that these components can work together to mitigate the effects of a collision and prevent override. A series of dynamic CEM coupling tests is planned which will demonstrate that the push-back coupler will, or will not, trigger, depending on the proper conditions. However, before the robustness of a push-back coupler is demonstrated, a baseline for conventional coupling must be established to determine the maximum non-destructive conventional coupling speed. Therefore, conventional coupling tests were conducted. The coupling tests were conducted repeatedly with the same F40 locomotive and M1 passenger car, starting at 2 mph for the first test, and increasing in increments of 2 mph until damage occurred in the vehicles.

1.2 Objectives

This effort determined the maximum nondestructive conventional coupling speed by conducting conventional coupling tests. This established a baseline for comparison with future CEM coupling tests. The objective of the test was to measure and characterize the structural performance of the conventional coupler and the coupling vehicles under a range of dynamic coupling speeds until damage occurred in the vehicles.

1.3 Overall Approach

The overall approach for this test program was to repeatedly impact a standing passenger coach with a moving F40 locomotive to determine the threshold speed at which significant structural damage to one or both of the colliding vehicles was observed.

1.4 Scope

The scope of the test program described in this report was limited to repeated collisions between an F40 passenger locomotive and a standing M1 passenger car at successively increasing speeds. Each vehicle was instrumented in order to derive certain data related to its dynamic response.

1.5 Organization of the Report

The report is organized in a simple fashion to facilitate the reader's understanding of how the tests were performed:

[Section 1](#) provides the background and objectives of the test program, describes the passenger equipment involved in the testing and general information about the test setup.

[Section 2](#) describes the extensive test instrumentation applied to each vehicle and the data acquisition system used to collect it, all of which is necessary to capture the dynamic equipment response for further analysis after the test.

[Section 3](#) provides the results (as derived from the instrumentation) for each of the test impacts at successively greater speed, as well as a description of the damage to the colliding vehicles observed as the test progressed.

[Section 4](#) provides the conclusions drawn from this impact test series.

[Appendices A](#) through [G](#) describe the data collected for each impact event.

1.6 M1 Car

The M1 car is an electric multiple unit vehicle, built by the Budd Company for the Long Island Railroad. The testers chose M1 car 9324 to serve as a stationary passenger car. The weight of this car was 73,325 pounds. This car suffered previous fire damage on the cab end. Some of the composite material used outside and inside of the cab was burned; however, inspection showed there was no significant damage to the car structure. All interior equipment including floor, seats, and side wall panels was removed before the testing, and the car's asbestos contamination was abated. [Figure 1](#) has a picture of M1 car 9324. Missing traction bars were replaced with 1-inch diameter solid steel rods.



Figure 1. M1 Car 9324

1.7 F40 Locomotive

The F40 locomotive was a four-axle diesel electric locomotive intended for use in passenger service. These tests used F40 locomotive 202 as the impacting vehicle. The weight of this locomotive was 245,800 pounds. [Figure 2](#) has a picture of F40 locomotive 202.



Figure 2. F40 Locomotive

1.8 Test Setup

The conventional coupling testing was performed on November 18 and 19, 2015, at the Transportation Technology Center (TTC) in Pueblo, CO. In each test, the F40 locomotive was positioned uphill from the stationary M1 car and allowed to roll into the car. The locomotive's release positions were determined through speed trials and adjusted shortly before the release to achieve the desired impact speed. The couplers of the locomotive and M1 car were opened and aligned, to allow the M1 car and locomotive to couple upon impact.

The M1 car's air brakes were applied and the hand brake was secured before each impact. The M1 car's front coupler was placed at the predesignated point of impact before each test run. A string of loaded hopper cars was placed roughly 200 feet behind the M1 to arrest any remaining momentum after each impact.

Before the testing, two separate speed trials were conducted using the F40 locomotive to determine the optimum release location for each impact speed. To determine a more precise release location for each target speed, data from these speed runs was used in calculations which considered wind speed and direction.

2. Test Instrumentation

2.1 Overview

The test configuration and instrumentation were consistent with the specifications from the test implementation plan. [Table 1](#) lists all the instrumentation used for this testing. Additional descriptions of instrumentation are provided in the following subsections.

Table 1. Instrumentation Summary

Type of Instrumentation	Channel Count
Accelerometers	34
String Potentiometers	16
Total Data Channels	50
High Definition Video	4
High Speed Video	6

2.2 Definition of Coordinate Axes

All local acceleration and displacement coordinate systems are defined relative to the front (lead) end of the 202 locomotive. Positive X, Y, and Z directions are forward, left, and up relative to the lead end of the locomotive and facing the direction of travel.

2.3 Locomotive Accelerometers and String Potentiometers

Tri-axial accelerometers were placed at the two ends and the center along the locomotive center line. The locomotive had longitudinal and vertical accelerometers placed on the left and right sides of its underframe at its longitudinal center. Each locomotive truck was equipped with a vertical accelerometer. The locomotive's coupler was fitted with two longitudinal accelerometers, one on the left side, and one on the right. The typical scale factor calibration error for the accelerometers used was 2 percent. In addition to these accelerometers, the locomotive was instrumented with string potentiometers across each truck's secondary suspension. String potentiometers were also fitted to the coupler of the locomotive to measure the up/down and left/right displacements of the coupler. The underframe of the locomotive was fitted with a string potentiometer near the coupler to measure longitudinal displacement. This instrumentation plan is summarized in [Table 2](#) and [Figure 3](#) through [Figure 7](#).

Table 2. Locomotive Instrumentation

Name	Range	Location
<i>ALLE_X</i>	400 g	Locomotive, lead end, center – longitudinal
<i>ALLE_Y</i>	200 g	Locomotive, lead end, center – lateral
<i>ALLE_Z</i>	200 g	Locomotive, lead end, center – vertical
<i>ALUC_X</i>	200 g	Locomotive, underframe center – longitudinal
<i>ALUC_Y</i>	200 g	Locomotive, underframe center – lateral
<i>ALUC_Z</i>	200 g	Locomotive, underframe center – vertical
<i>ALUCR_X</i>	200 g	Locomotive, underframe center right – longitudinal
<i>ALUCR_Z</i>	200 g	Locomotive, underframe center right – vertical
<i>ALUCL_X</i>	200 g	Locomotive, underframe center left – longitudinal
<i>ALUCL_Z</i>	200 g	Locomotive, underframe center left – vertical
<i>ALTEC_X</i>	200 g	Locomotive, trailing end, center – longitudinal
<i>ALTEC_Y</i>	200 g	Locomotive, trailing end, center – lateral
<i>ALTEC_Z</i>	200 g	Locomotive, trailing end, center – vertical
<i>ALLT_Z</i>	400 g	Locomotive, lead truck – vertical
<i>ALTT_Z</i>	400 g	Locomotive, trailing truck – vertical
<i>ALCR_X</i>	5,000 g	Locomotive coupler, right
<i>ALCL_X</i>	5,000 g	Locomotive coupler, left
<i>DLLTR</i>	+/- 5 inch	Locomotive secondary suspension, lead truck, right
<i>DLLTL</i>	+/- 5 inch	Locomotive secondary suspension, lead truck, left
<i>DLTTR</i>	+/- 5 inch	Locomotive secondary suspension, trailing truck, right
<i>DLTTL</i>	+/- 5 inch	Locomotive secondary suspension, trailing truck, left
<i>DLU</i>	+5/-45 inch	Locomotive underframe, front – longitudinal
<i>DLC_X</i>	+20/-30 inch	Locomotive coupler – longitudinal
<i>DLC_Y</i>	+/- 25 inch	Locomotive coupler – lateral
<i>DLC_Z</i>	+/- 25 inch	Locomotive coupler – vertical

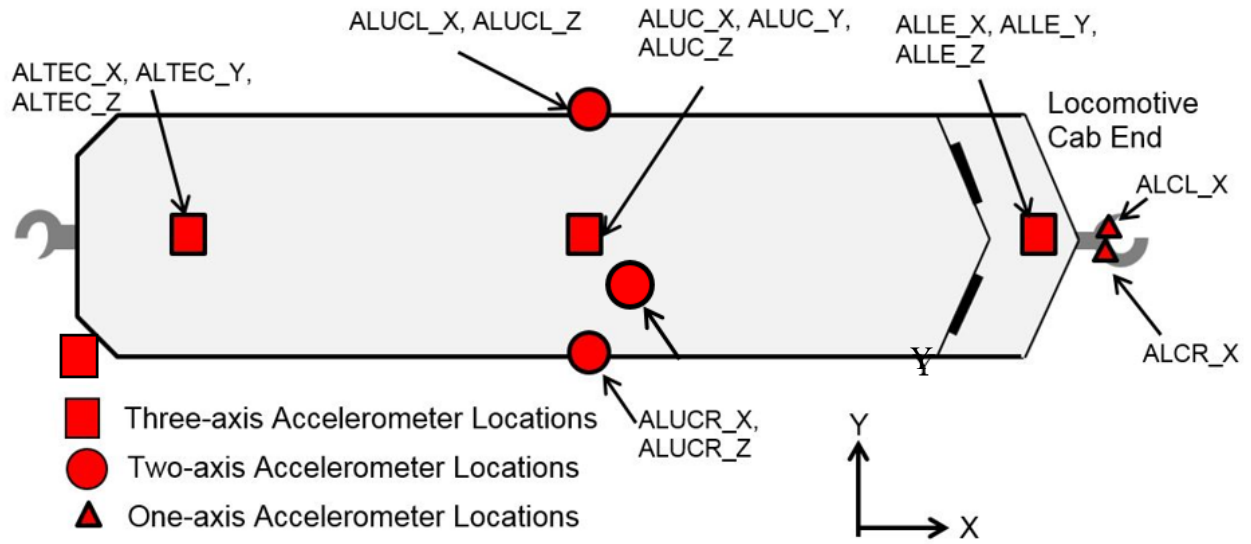


Figure 3. Accelerometer Locations on F40 Locomotive



Figure 4. Locomotive Truck

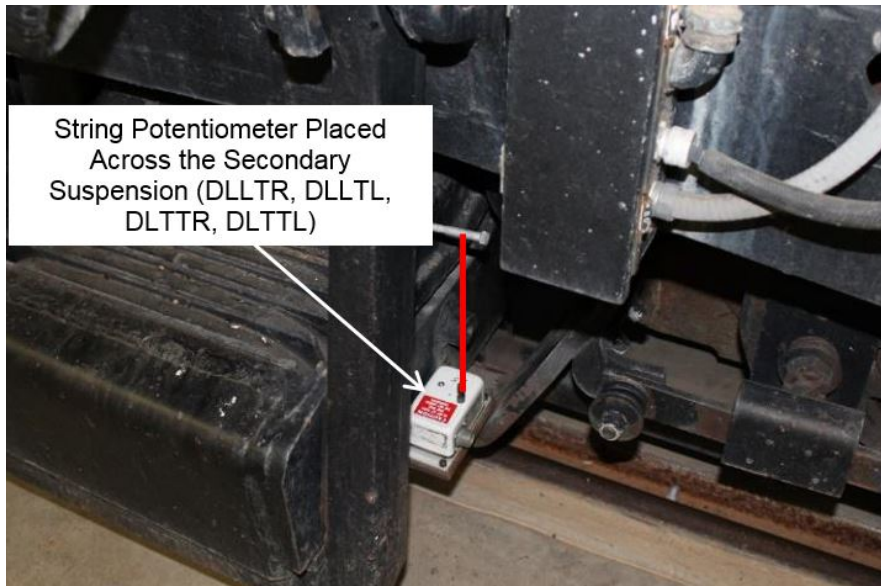


Figure 5. Locomotive Truck Secondary Suspension

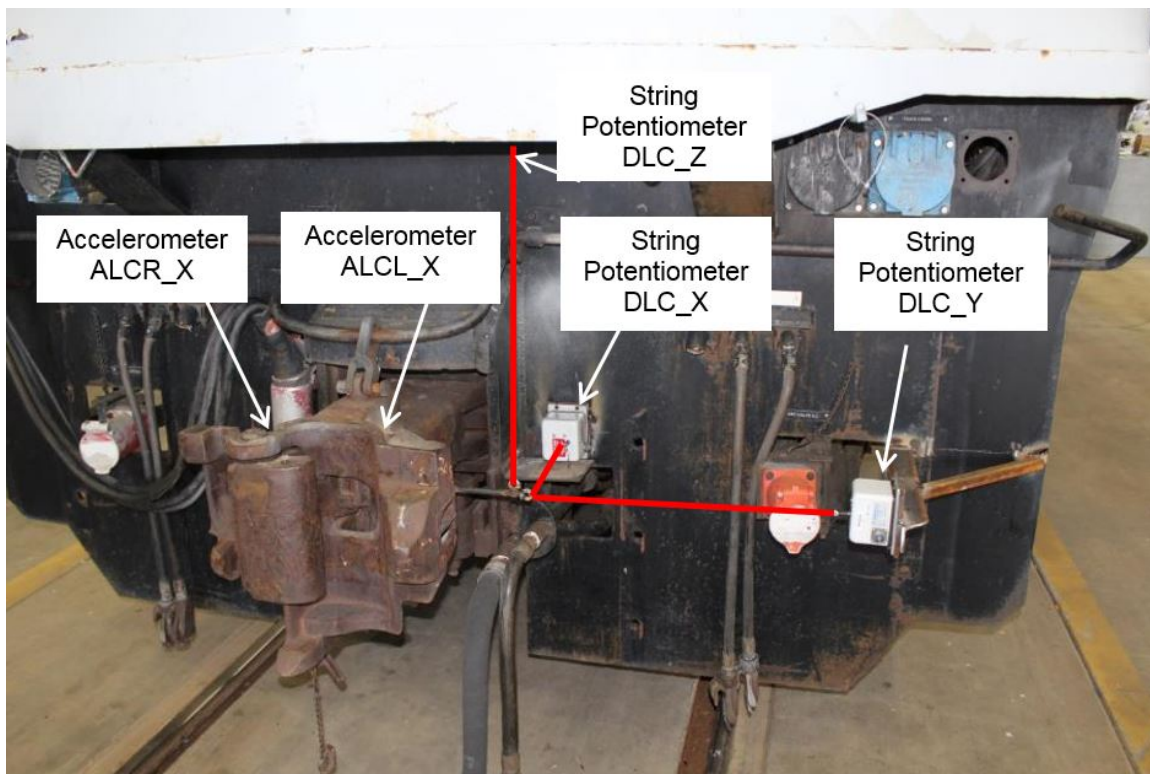


Figure 6. Locomotive Coupler Instrumentation



Figure 7. Locomotive Underframe String Potentiometer

2.4 Locomotive Speed Sensors

Multiple speed sensors accurately measured the impact speed of the locomotive when it was within 20 inches of the impact point. The speed trap is a reflector-based sensor. It used ground-based reflectors separated by a known distance and a vehicle-based light sensor that triggered as the locomotive passes over the reflectors. The last reflector was within 10 inches of the impact point. The time interval between passing the reflectors was recorded and speed was calculated from distance and time. Backup speed measurements were made with a handheld radar gun.

2.5 M1 Car Accelerometers and String Potentiometers

Tri-axial accelerometers were placed at the two ends and the center along the car center line. The car had longitudinal and vertical accelerometers placed on the left and right side of its underframe at its center. Each truck was fitted with a vertical accelerometer. The car's coupler was fitted with two longitudinal accelerometers, one on the left side and one on the top. The typical scale factor calibration error for the accelerometers used was 2 percent. In addition to these accelerometers, the M1 car was fitted with string potentiometers across each truck's secondary suspension. String potentiometers were also fitted to the coupler of the M1 car to measure the up/down and left/right displacements of the coupler. The underframe of the car was also fitted with a string potentiometer near the coupler to measure longitudinal displacement. This instrumentation plan is summarized in [Table 3](#) and [Figure 8](#) through [Figure 11](#).

Table 3. M1 Car Instrumentation

Name	Range	Location
<i>AMLE_X</i>	400 g	M1 car, lead end, center – longitudinal
<i>AMLE_Y</i>	200 g	M1 car, lead end, center – lateral
<i>AMLE_Z</i>	200 g	M1 car, lead end, center – vertical
<i>AMUC_X</i>	200 g	M1 car, underframe center – longitudinal
<i>AMUC_Y</i>	200 g	M1 car, underframe center – lateral
<i>AMUC_Z</i>	200 g	M1 car, underframe center – vertical
<i>AMUCR_X</i>	200 g	M1 car, underframe center right – longitudinal
<i>AMUCR_Z</i>	200 g	M1 car, underframe center right – vertical
<i>AMUCL_X</i>	200 g	M1 car, underframe center left – longitudinal
<i>AMUCL_Z</i>	200 g	M1 car, underframe center left – vertical
<i>AMTEC_X</i>	200 g	M1 car, trailing end, center – longitudinal
<i>AMTEC_Y</i>	200 g	M1 car, trailing end, center – lateral
<i>AMTEC_Z</i>	200 g	M1 car, trailing end, center – vertical
<i>AMLT_Z</i>	400 g	M1 car, lead truck – vertical
<i>AMTT_Z</i>	400 g	M1 car, trailing truck
<i>AMCR_X</i>	5,000 g	M1 car coupler, right
<i>AMCL_X</i>	5,000 g	M1 car coupler, left
<i>DMLTR</i>	+/- 5 inch	M1 car secondary suspension, lead truck, right
<i>DMLTL</i>	+/- 5 inch	M1 car secondary suspension, lead truck, left
<i>DMTTR</i>	+/- 5 inch	M1 car secondary suspension, trailing truck, right
<i>DMTTL</i>	+/- 5 inch	M1 car secondary suspension, trailing truck, left
<i>DMU</i>	+5/-45 inch	M1 car underframe, front – longitudinal
<i>DMC_X</i>	+20/-30 inch	M1 car coupler – longitudinal
<i>DMC_Y</i>	+/- 25 inch	M1 car coupler – lateral
<i>DMC_Z</i>	+/- 25 inch	M1 car coupler – vertical

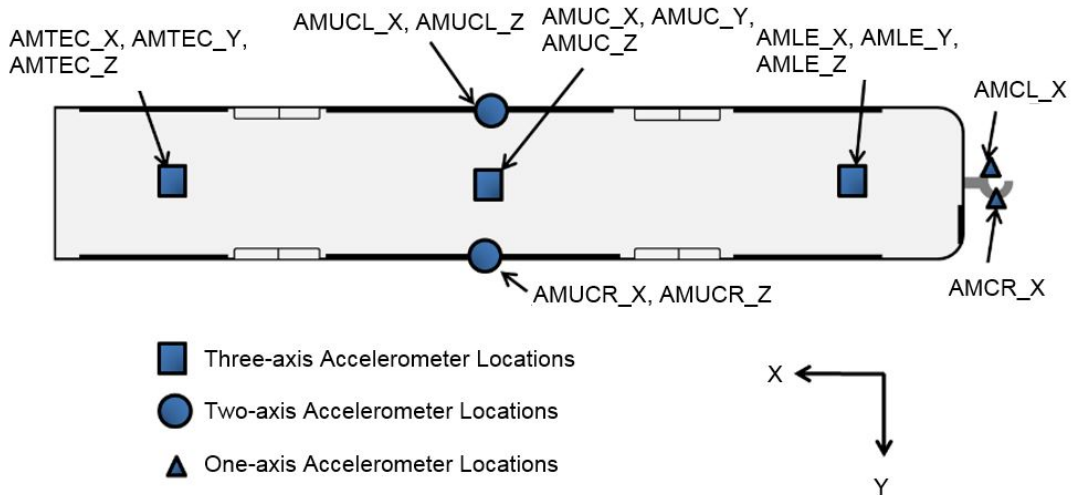


Figure 8. Accelerometer Locations on M1 Passenger Car

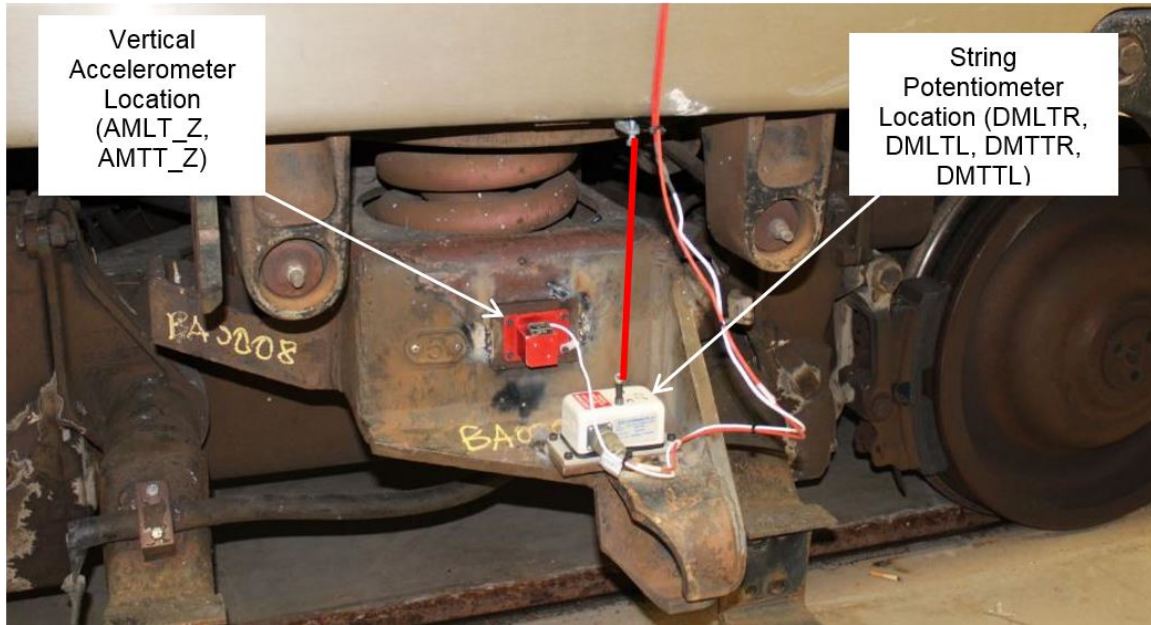


Figure 9. String Potentiometer and Accelerometer on M1 Car Truck

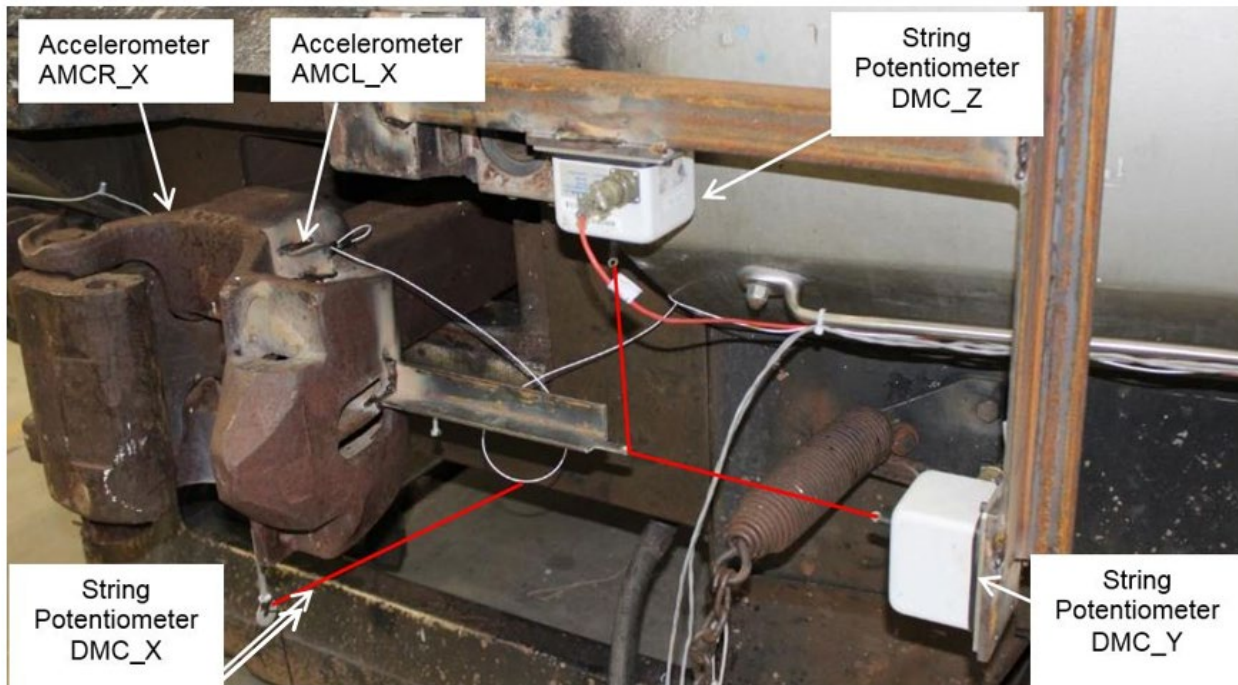


Figure 10. M1 Coupler Instrumentation

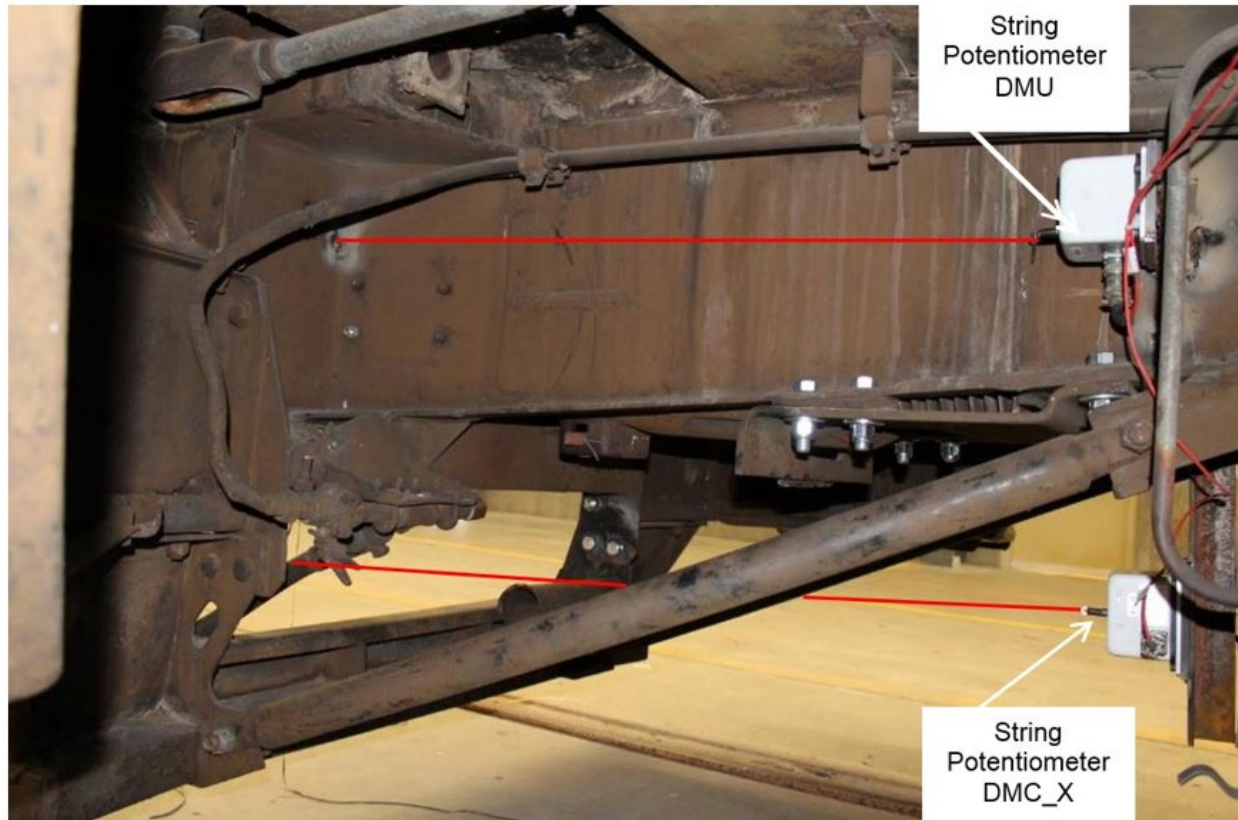


Figure 11. M1 Underframe

2.6 Real Time and High Speed Photography

Six high speed and four real-time high definition video cameras documented each impact event. [Figure 12](#) shows a schematic of the camera positions.

Final alignment and sighting of the cameras was done when the locomotive and M1 car were positioned at the impact point, before the start of each test. The two high definition cameras (shown in [Figure 12](#) in green) were attached to the fronts of the locomotive and M1 car and overlooked the couplers of each vehicle. In addition, during the 10 mph and 12 mph runs, an additional high definition camera was placed on the track underneath the M1 car's draft gear. This camera is not shown in [Figure 12](#).

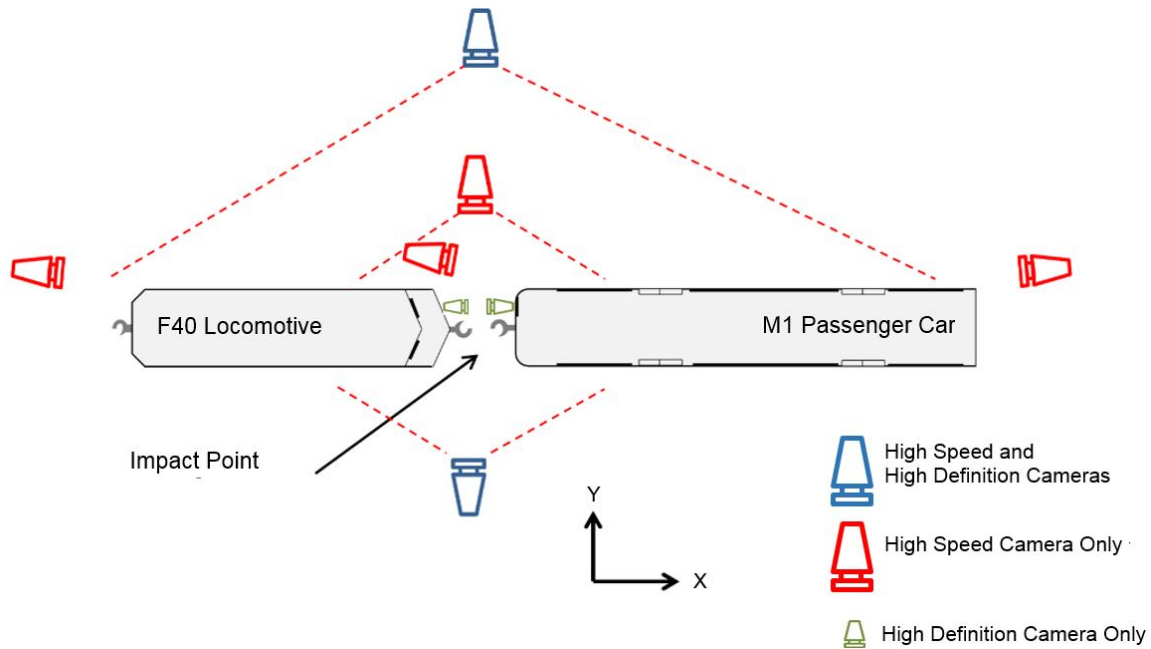


Figure 12. High Speed and Digital Camera Locations

2.7 Data Acquisition

A set of eight-channel battery-powered on-board data acquisition systems recorded data from the instrumentation mounted on the locomotive. These systems provided excitation to the instrumentation, analog anti-aliasing filtering of the signals, analog-to-digital conversion, and recording of each data stream. A similar set of data acquisition systems was installed onboard the M1 car.

The data acquisition systems are GMH Engineering Data BRICK Model III units. The data acquisition process complied with the appropriate sections of SAE J211. Data from each channel was anti-alias filtered at 1,735 Hz then sampled and recorded at 12,800 Hz. Data recorded on the Data BRICKS was synchronized to time zero at initial impact. The time reference came from closure of the tape switches on the front of the test vehicle. Each Data BRICK is ruggedized for shock loading up to at least 100 g. On-board battery power was provided by GMH Engineering 1.7 Amp-hour 14.4 Volt NiCad Packs. Tape Switches, Inc., model 1201-131-A tape switches registered event initial contact for each impact.

Software in the Data BRICK was used to determine zero levels and calibration factors rather than relying on set gains and expecting no zero drift. The Data BRICKS were set to record 1 second of data before initial impact and 7 seconds of data after initial impact.

3. Results

3.1 Test Conditions

As described in [Section 1](#), this test program included a series of coupling impacts between an F40 locomotive and an M1 car, performed on November 18 and 19, 2015. The target impact speeds were 2, 4, 6, 8, 10, and 12 mph. The M1 car's brakes were applied. Ambient conditions for all test runs are summarized in [Table 4](#).

Table 4. Summary of Ambient Conditions

Test Run	Time	Wind Speed (mph)	Gust Speed (mph)	Wind Direction	Temperature (°F)
2 mph	9:15 AM	9	21	NW	49
4 mph	10:50 AM	9	37	NW	56.6
6 mph	1:20 PM	34	37	N-NW	60
8 mph	3:00 PM				
10 mph		9	19	N	37.8
12 mph		7	19	W-SW	48

3.2 Details of Test

The actual impact speeds for all test runs are shown in [Table 5](#), which also includes the approximate impact forces and energy levels based on accelerometer data. Most of the observed test vehicle damage was sustained by the M1 car, with no significant damage sustained by the locomotive.

Table 5. Summary of Test Results

Test	Target impact speed (mph)	Actual impact speed (mph)	Approximate impact force (lb.)	Impact energy (ft-lb)
1	2	1.89	146,000	29,352
2	4	3.86	296,000	122,429
3	6	5.67	674,000	264,165
4	8	7.89	939,000	511,520
5	10	9.95	1,790,000	813,495
6	12	11.86	2,390,000	1,155,788

3.3 Measured Data

The collected data was processed for offset corrections, and filtering. The offset adjustment procedure ensured that the plotted and analyzed data only contained impact-related information and excluded electronic offsets or steady biases. In order to determine the offset, the data collected before impact were averaged. The offset was then subtracted from the entire data set for each channel. This post-test offset adjustment is independent of the pre-test offset adjustment made by the data acquisition system.

The post-test data filtering was accomplished with a phaseless four-pole digital filter algorithm that was consistent with the requirements of SAE J211 [1]. A 60 Hz channel frequency class filter was applied for the filtered acceleration data in this report. A brief summary of the measured data is provided in this section. [Appendix B](#) contains the plots of the filtered data from all transducers.

The longitudinal acceleration of the locomotive was one of the primary measurements made by the team, which used multiple accelerometers to capture the data from the locomotive. The locomotive acceleration was used to derive the impact energy and contact force between the locomotive and M1 car. The average longitudinal acceleration history from locomotive accelerometers ALLE_X, ALUC_X, and ALTEC_X is shown in [Figure 13](#) through [Figure 18](#). Impact accelerations are shown as positive in these graphs; however, during an impact, the locomotive is accelerated in the negative X direction based on the established coordinate system. During the 10 mph and 12 mph test runs, the locomotive and M1 car failed to couple, and the data for these runs show multiple secondary impacts.

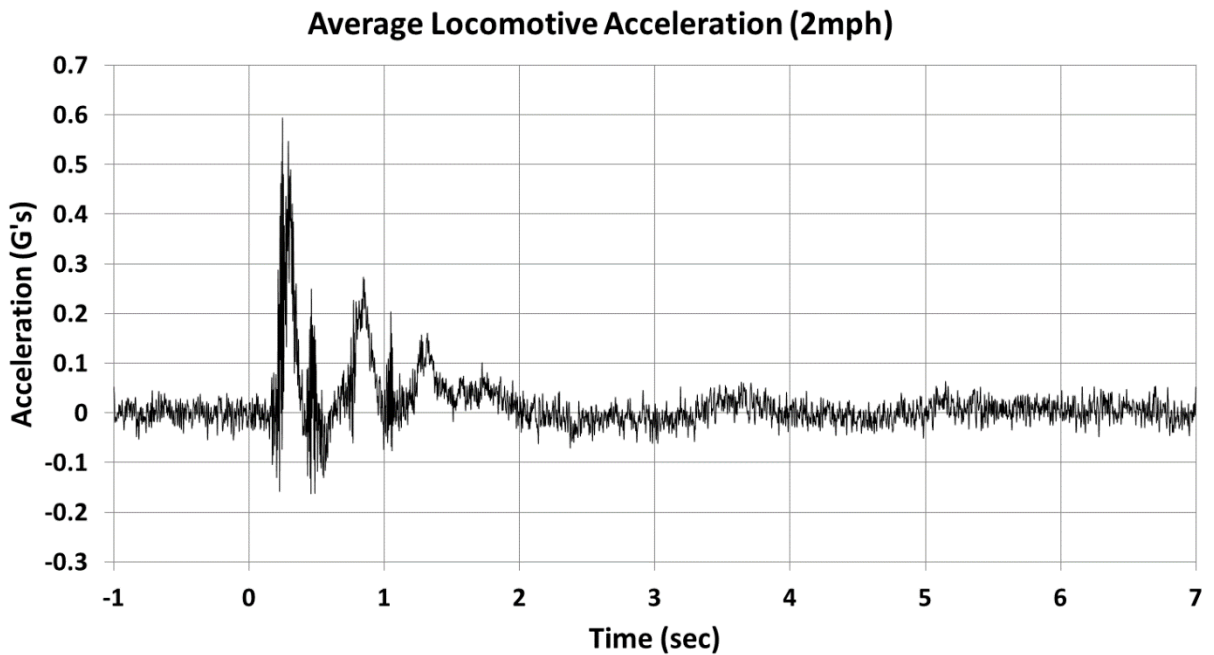


Figure 13. Longitudinal Locomotive Acceleration at 2 mph

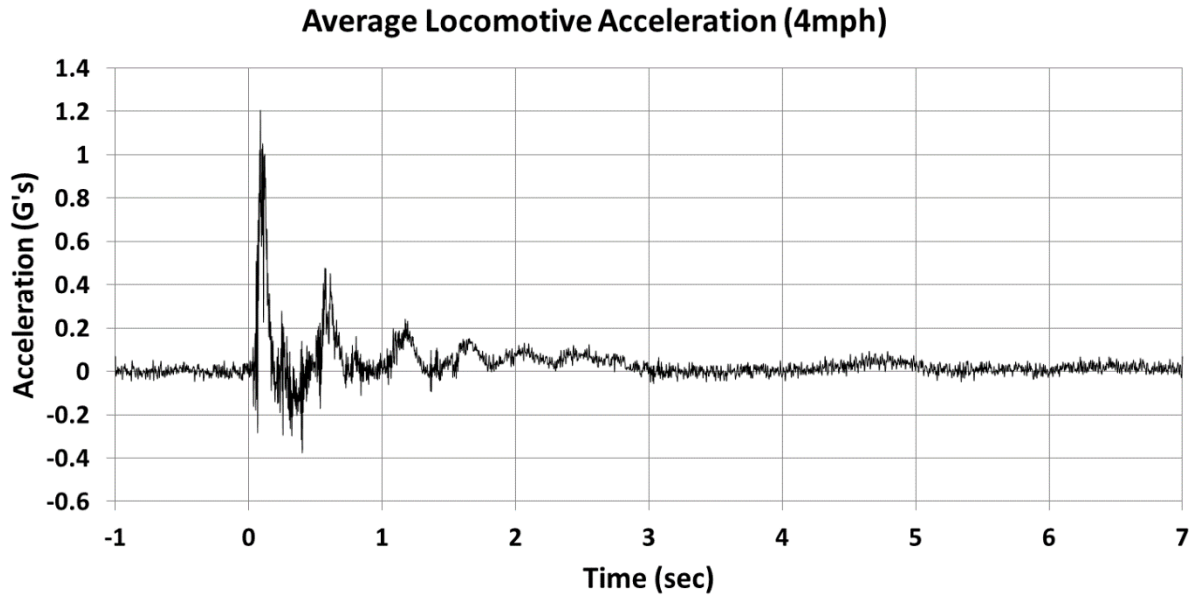


Figure 14. Longitudinal Locomotive Acceleration at 4 mph

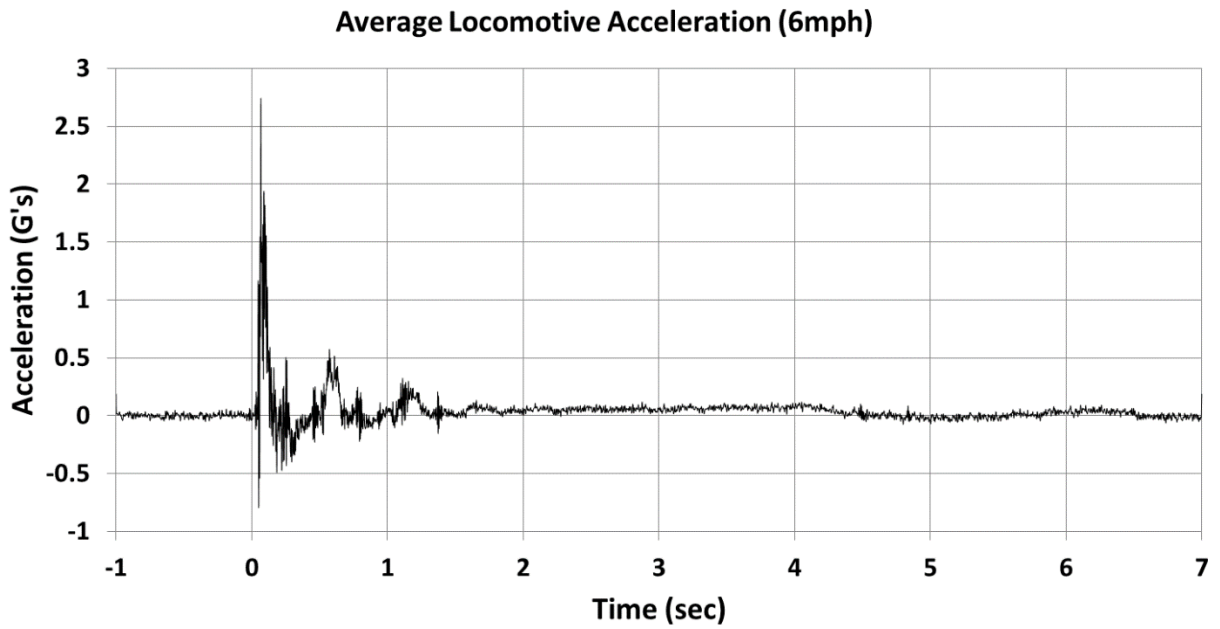


Figure 15. Longitudinal Locomotive Acceleration at 6 mph

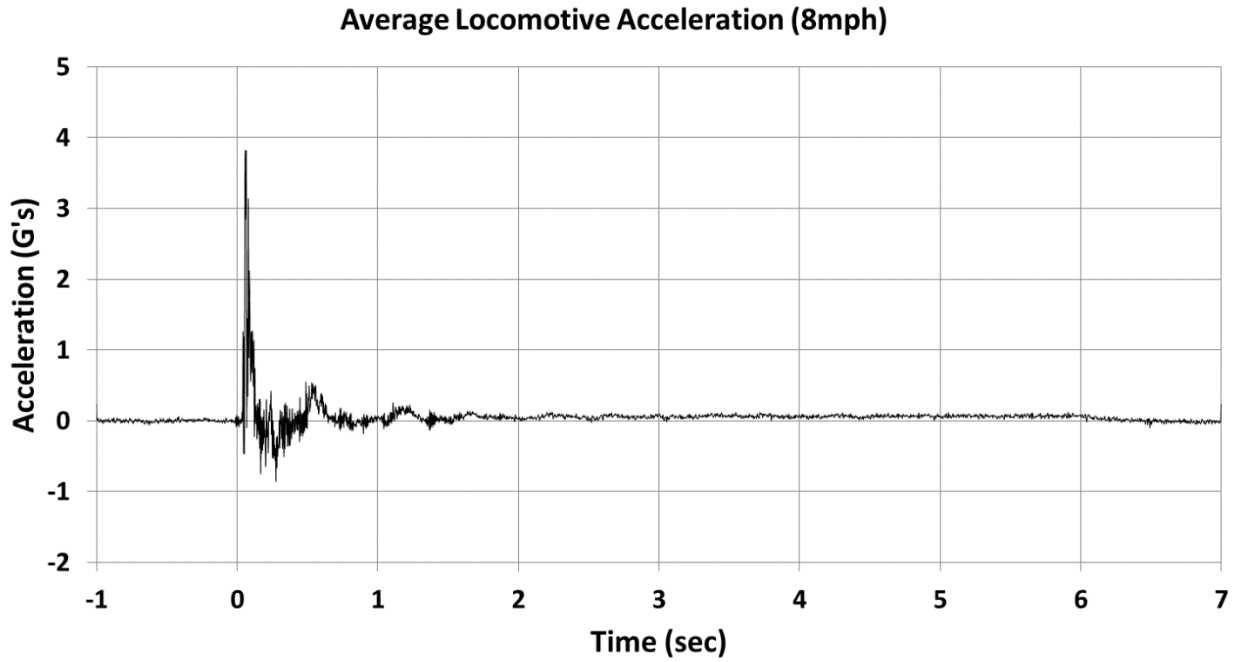


Figure 16. Longitudinal Locomotive Acceleration at 8 mph

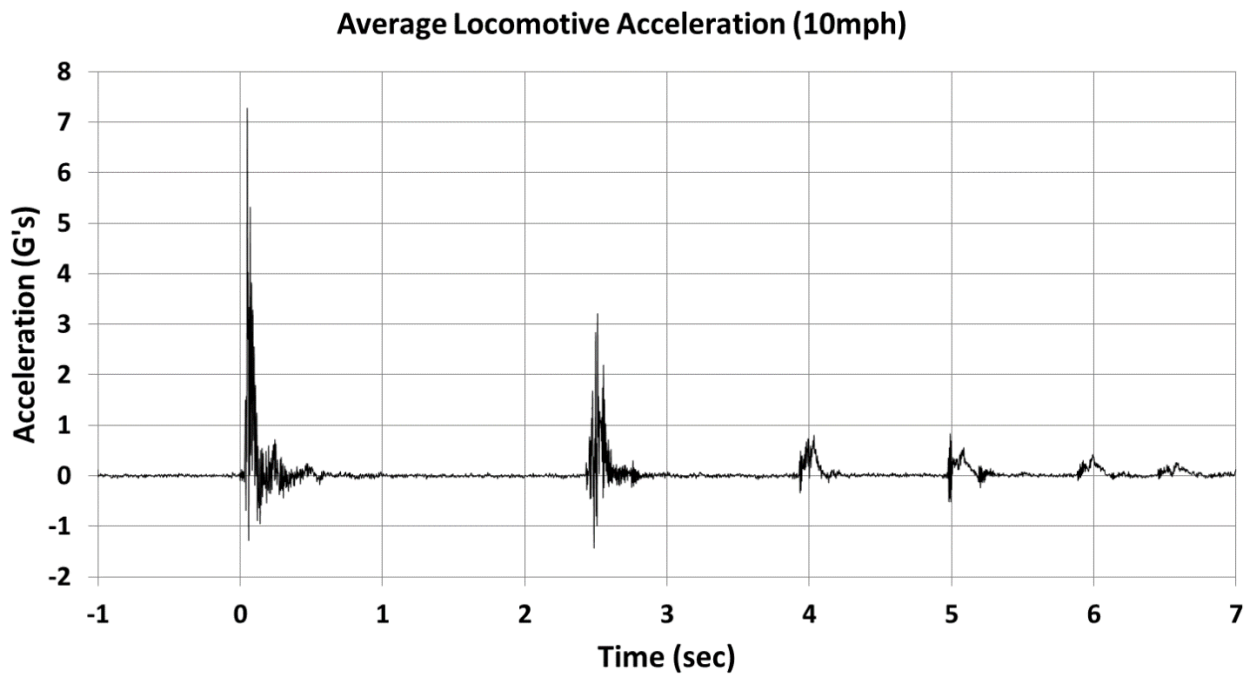


Figure 17. Longitudinal Locomotive Acceleration at 10 mph

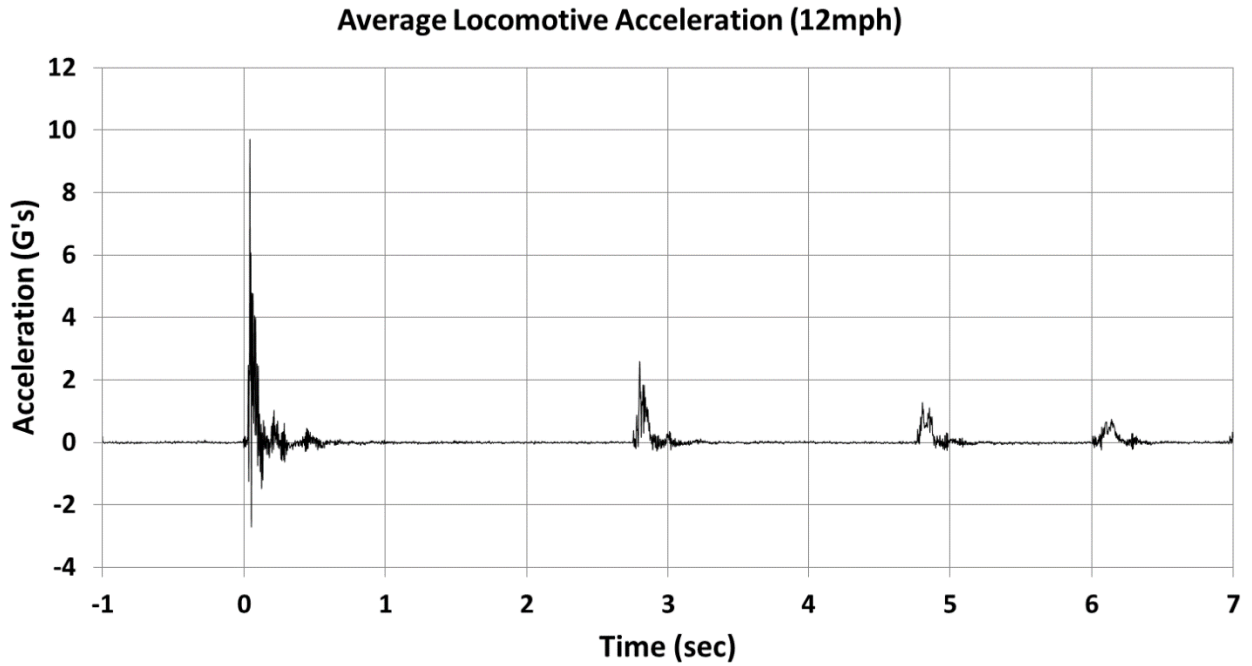


Figure 18. Longitudinal Locomotive Acceleration at 12 mph

Contact forces between the locomotive and coach car can be calculated as a product of the average acceleration and mass of the locomotive. [Figure 19](#) through [Figure 24](#) show the force history.

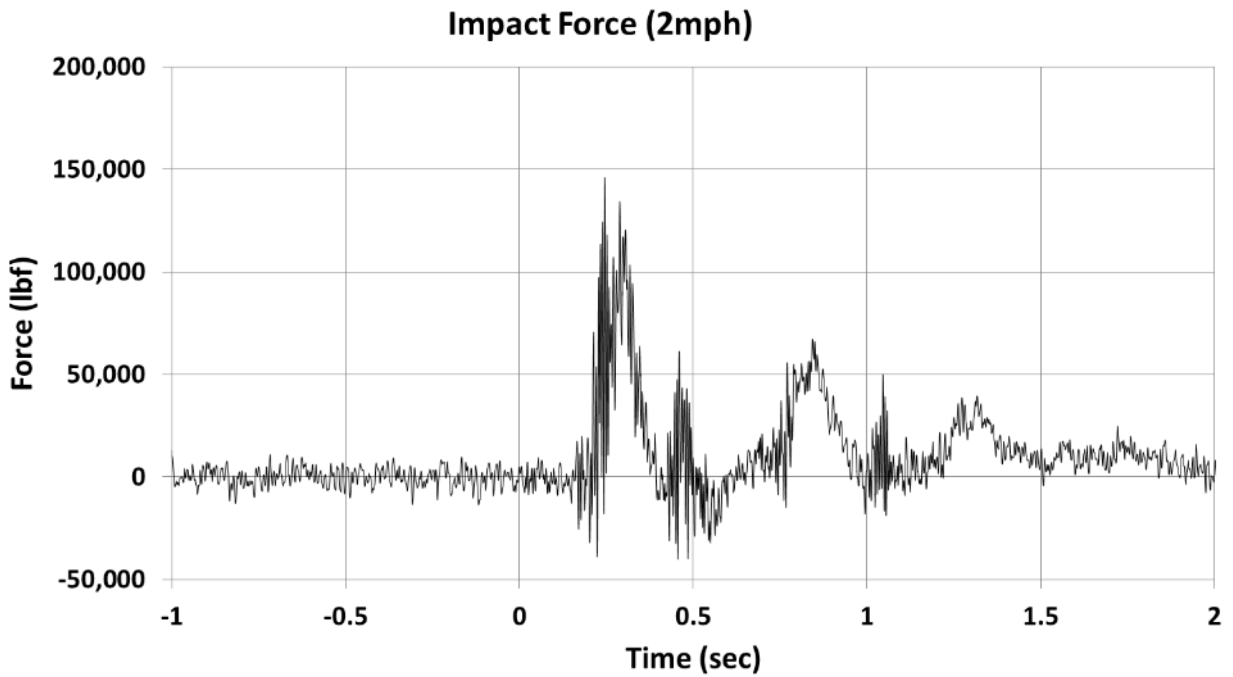


Figure 19. Impact Force at 2 mph

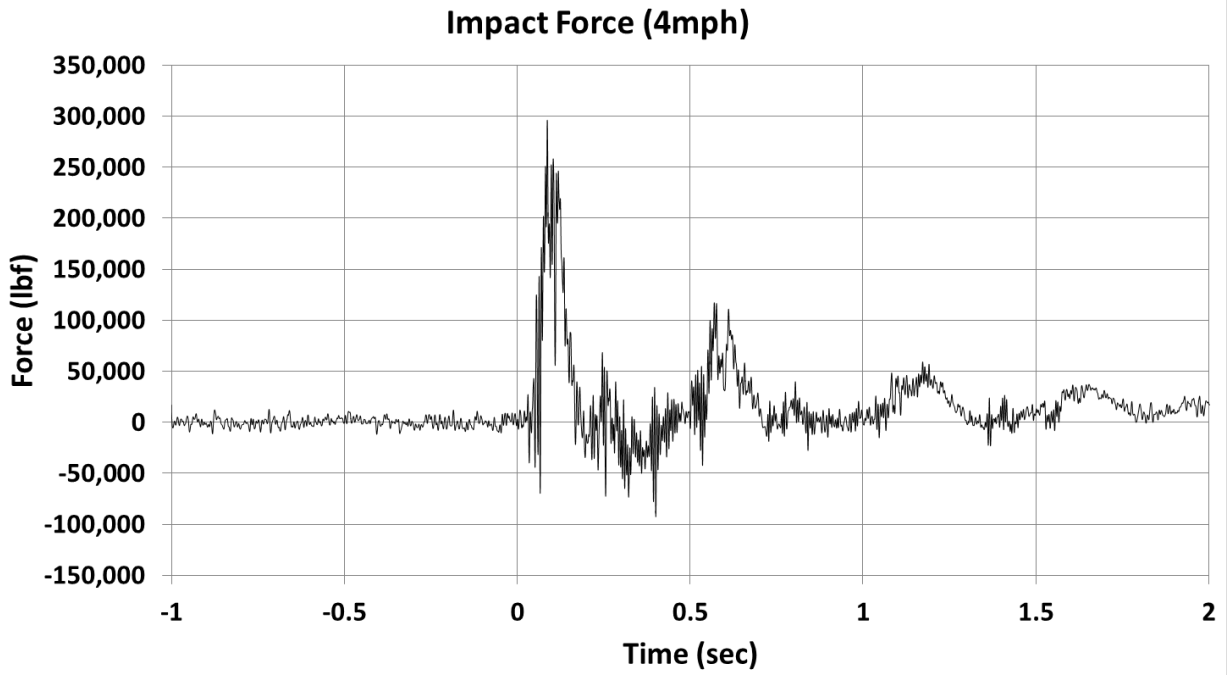


Figure 20. Impact Force at 4 mph

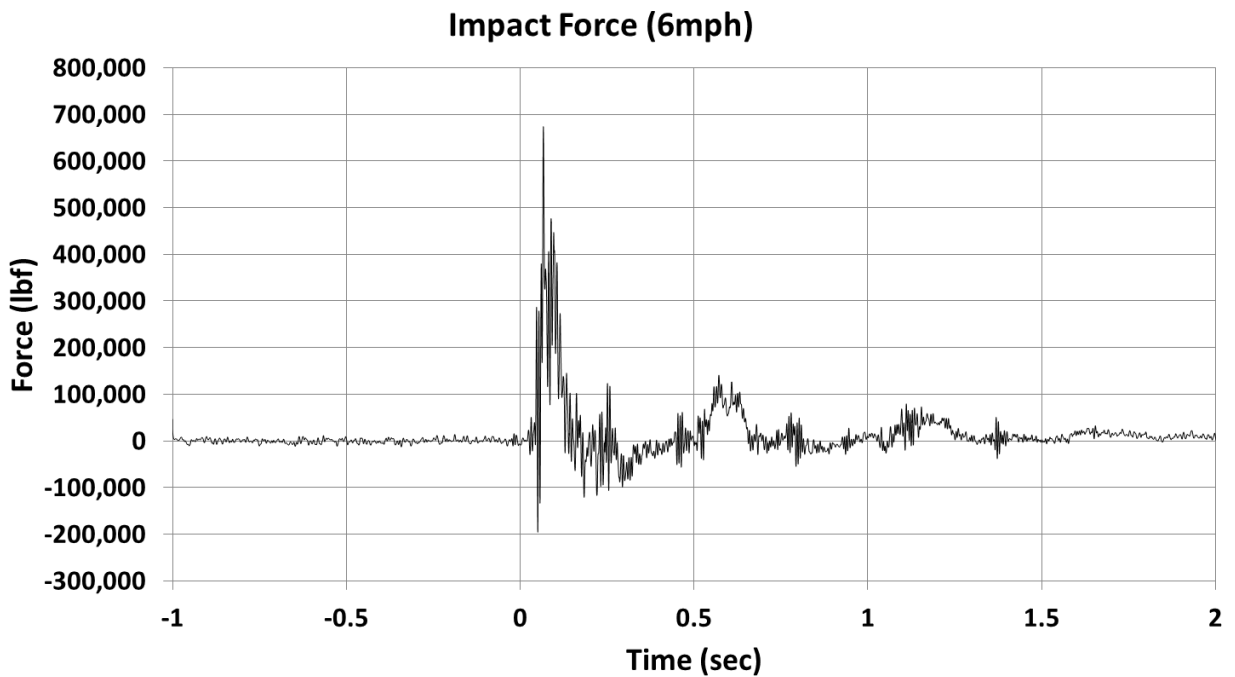


Figure 21. Impact Force at 6 mph

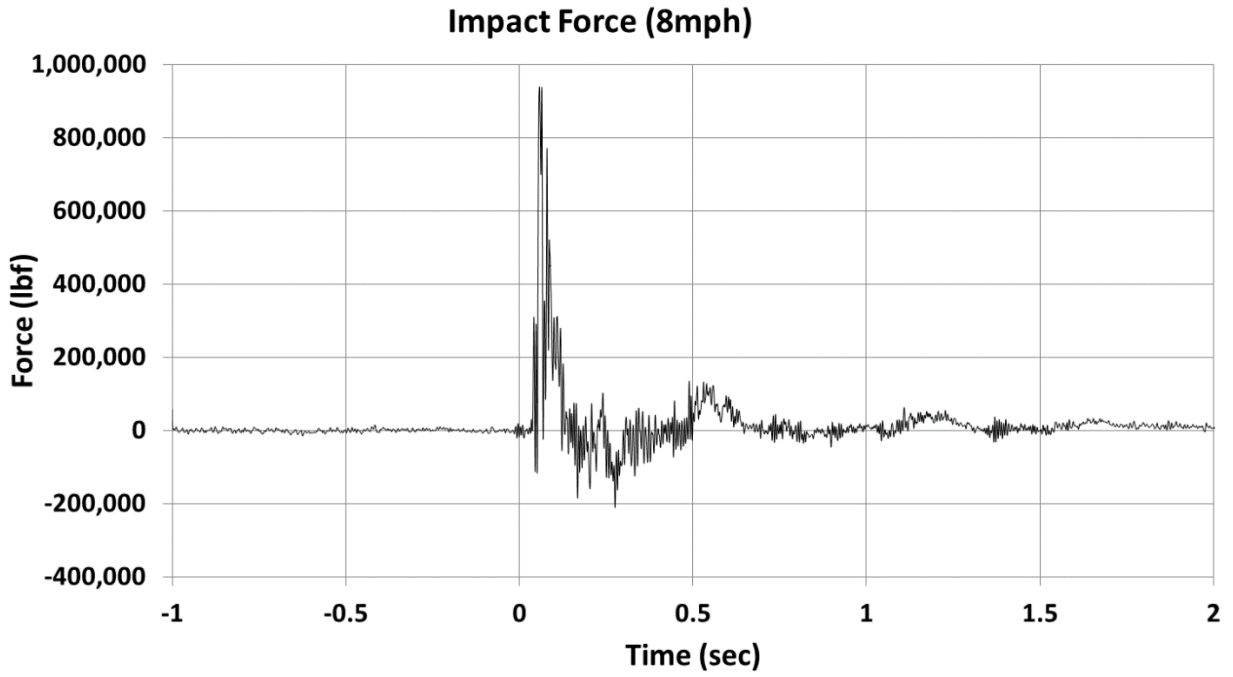


Figure 22. Impact Force at 8 mph

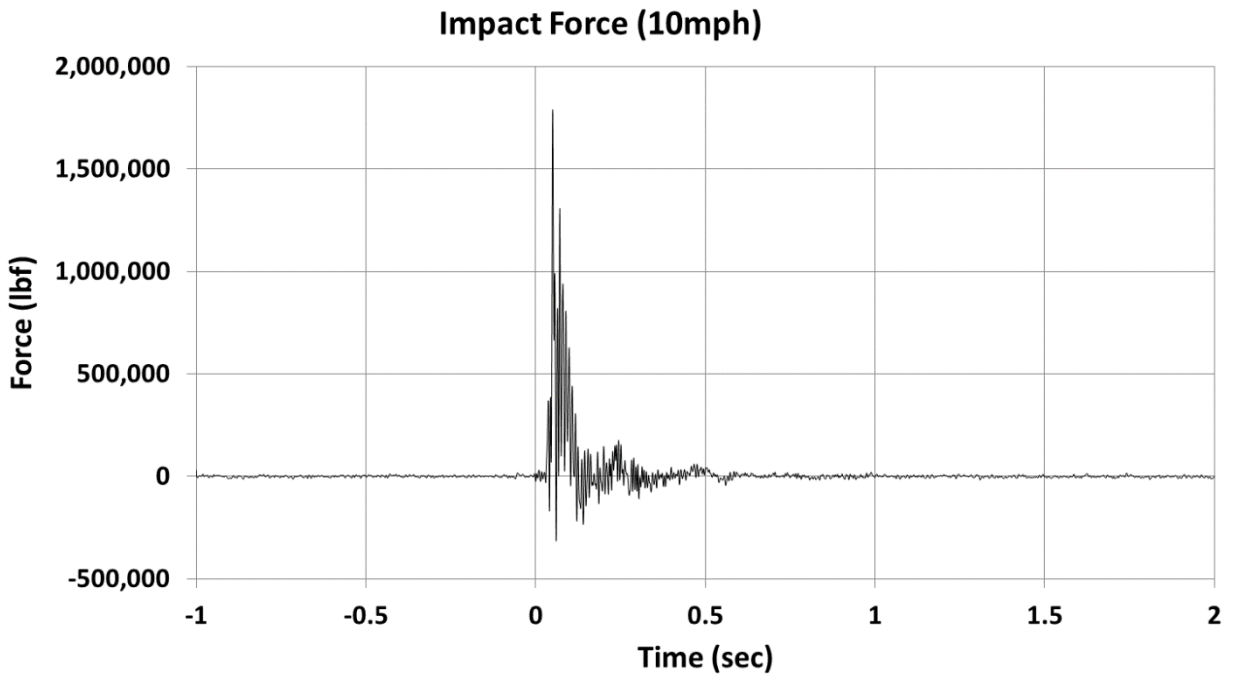


Figure 23. Impact Force at 10 mph

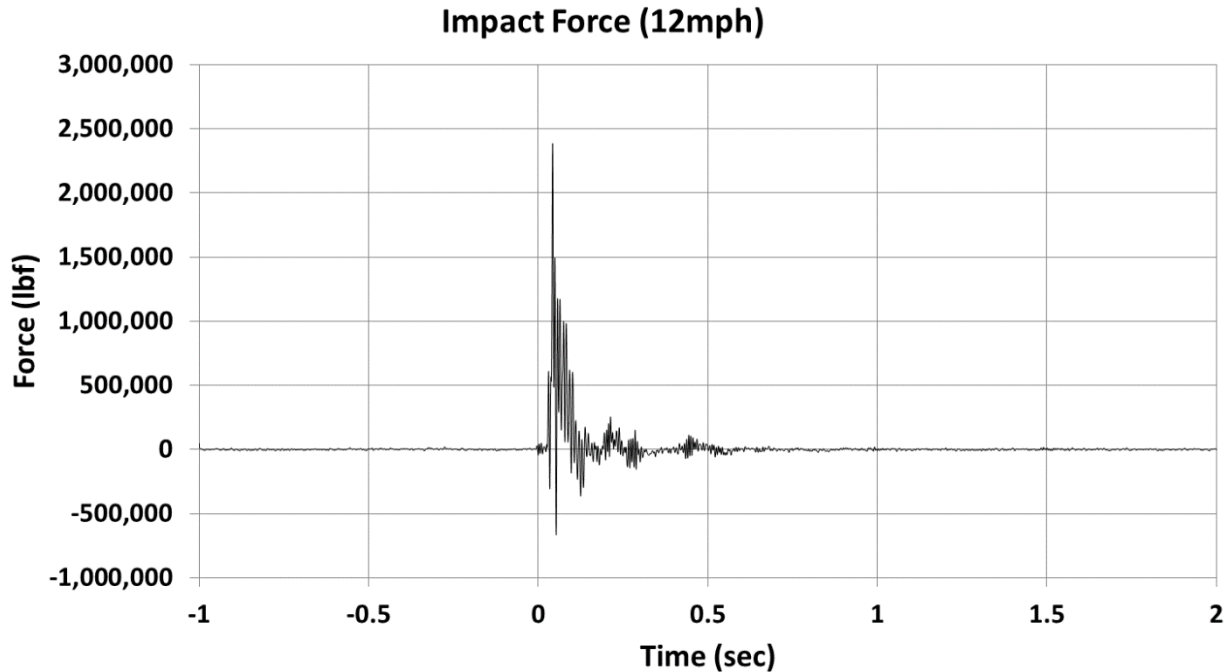


Figure 24. Impact Force at 12 mph

Integrating the acceleration history yields the velocity history for each trial run. Impact energy was then calculated using the velocity histories and the mass of the locomotive. Figure 25 through Figure 30 are graphs of the energy absorbed and the energy of the locomotive during each impact. The kinetic energy of the locomotive was calculated by subtracting the absorbed kinetic energy from the locomotive's maximum kinetic energy. The maximum kinetic energy was based on the locomotive's speed just before impact, as measured by the speed traps, and it is shown in Table 5. Theoretically, the kinetic energy of the locomotive should approach zero because all the energy the locomotive contained before impact would be dissipated by the time the locomotive came to a stop. The negative kinetic energies for the 2 mph through 8 mph runs occurred because the impacts took place on an incline, and the locomotive and M1 car had to move various distances before coming to a stop.

Thus, energy was added to the locomotive after each impact occurred, and that energy cannot be taken into account when the maximum kinetic energy of the locomotive is calculated without knowing the distance the locomotive traveled after impact. During the 10 mph and 12 mph runs, the locomotive energy did not reach zero, because data recording stopped before the locomotive came to a complete stop.

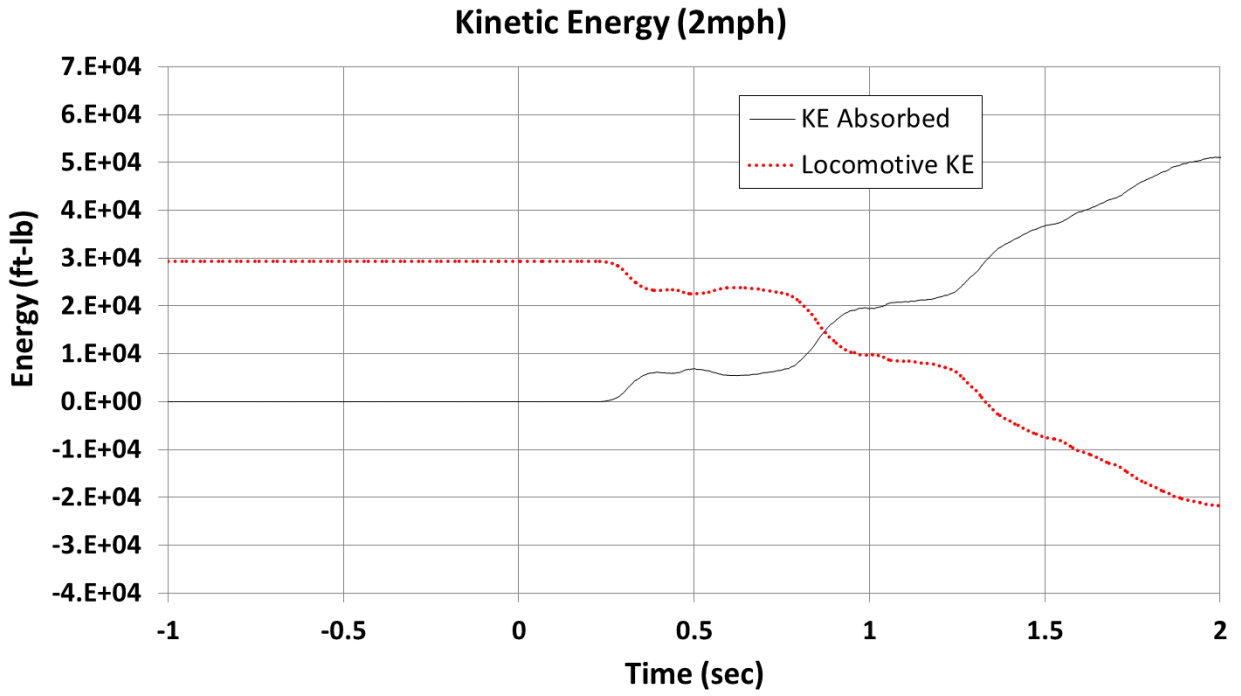


Figure 25. Impact Energy at 2 mph

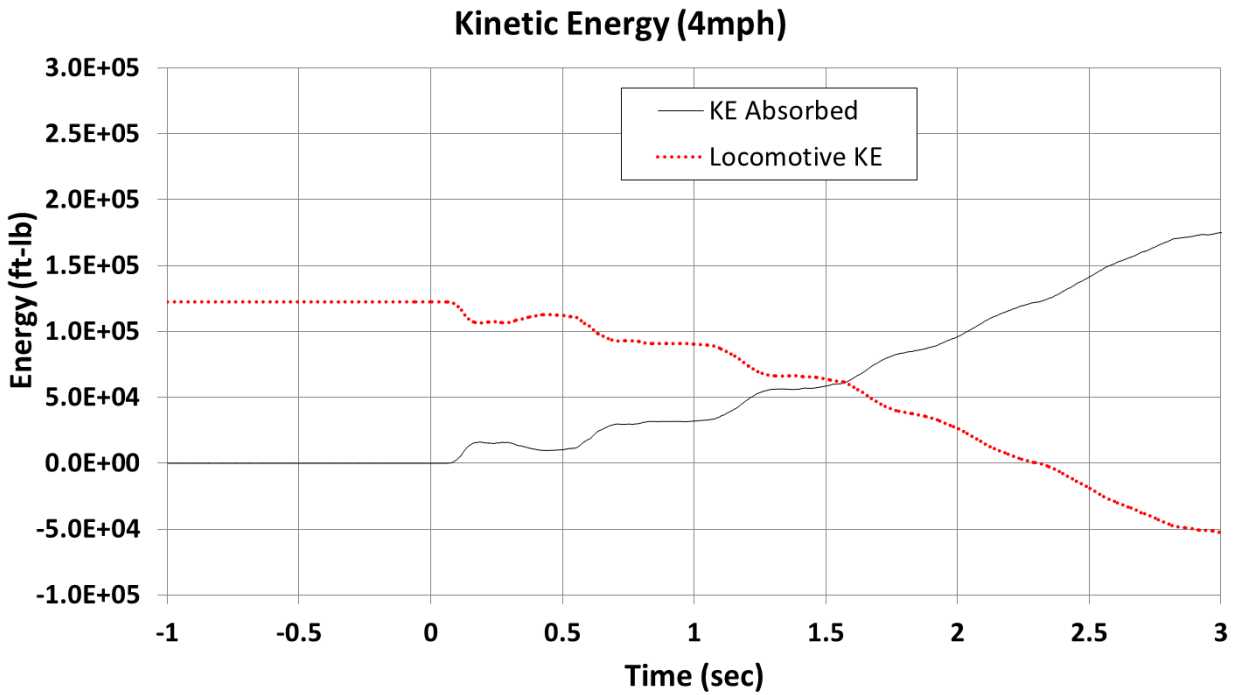


Figure 26. Impact Energy at 4 mph

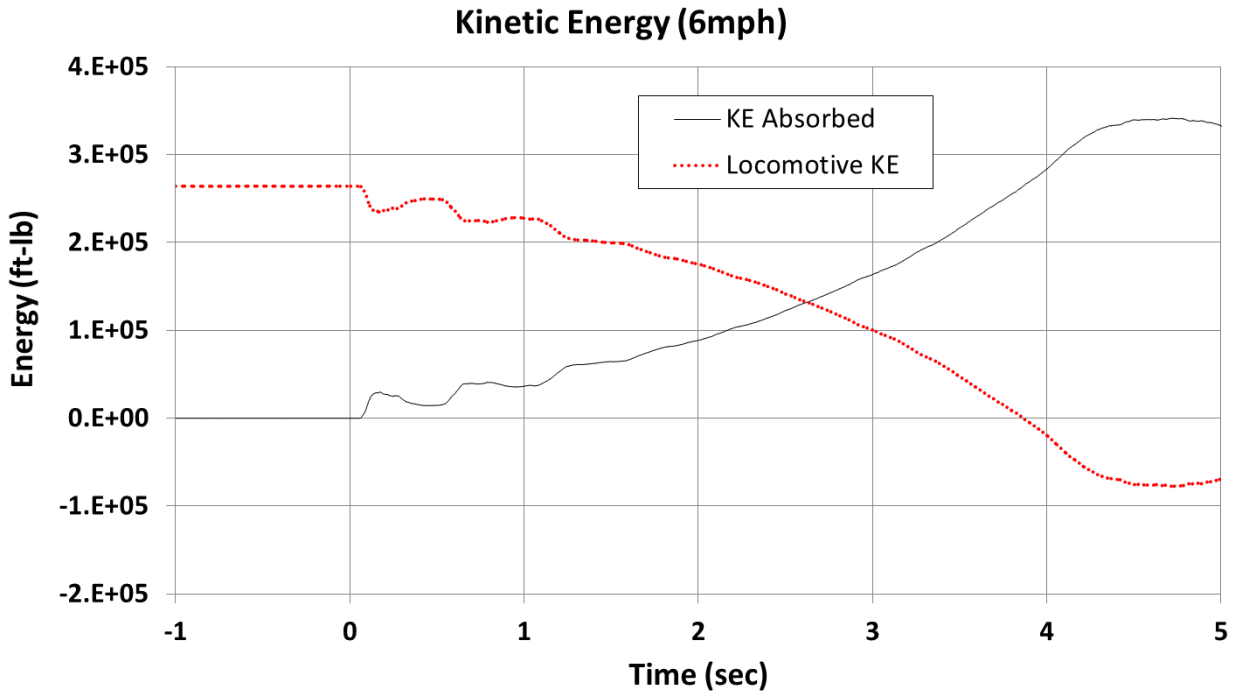


Figure 27. Impact Energy at 6 mph

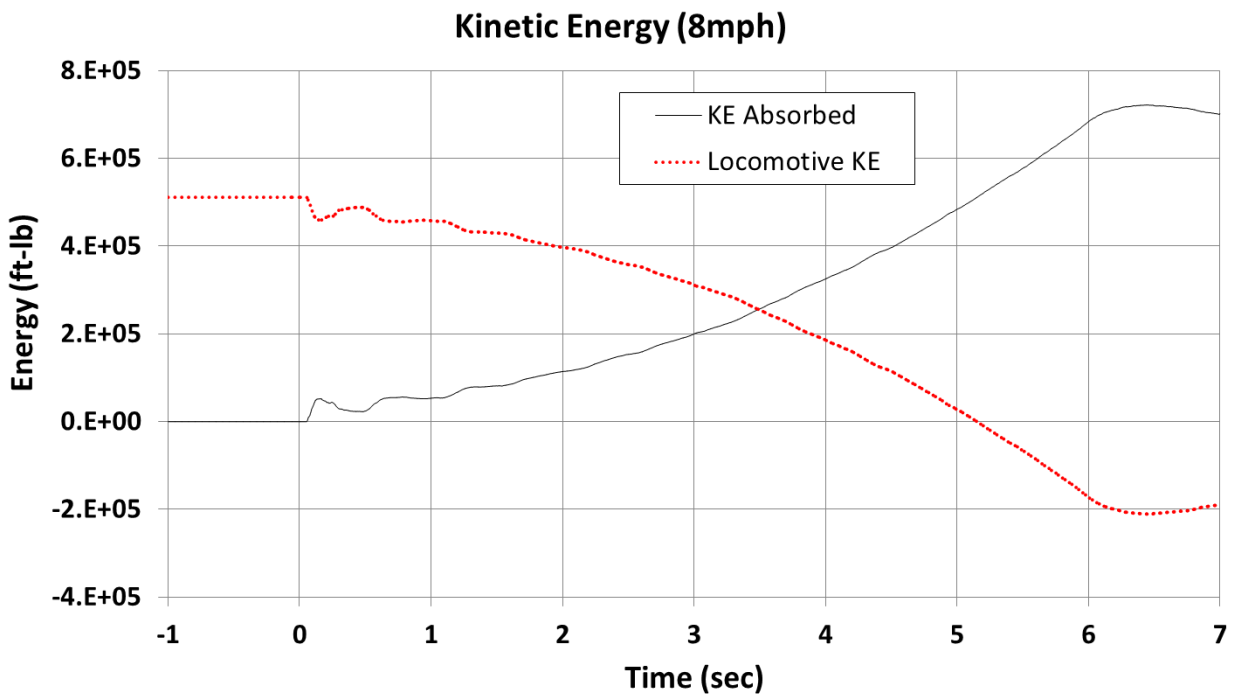


Figure 28. Impact Energy at 8 mph

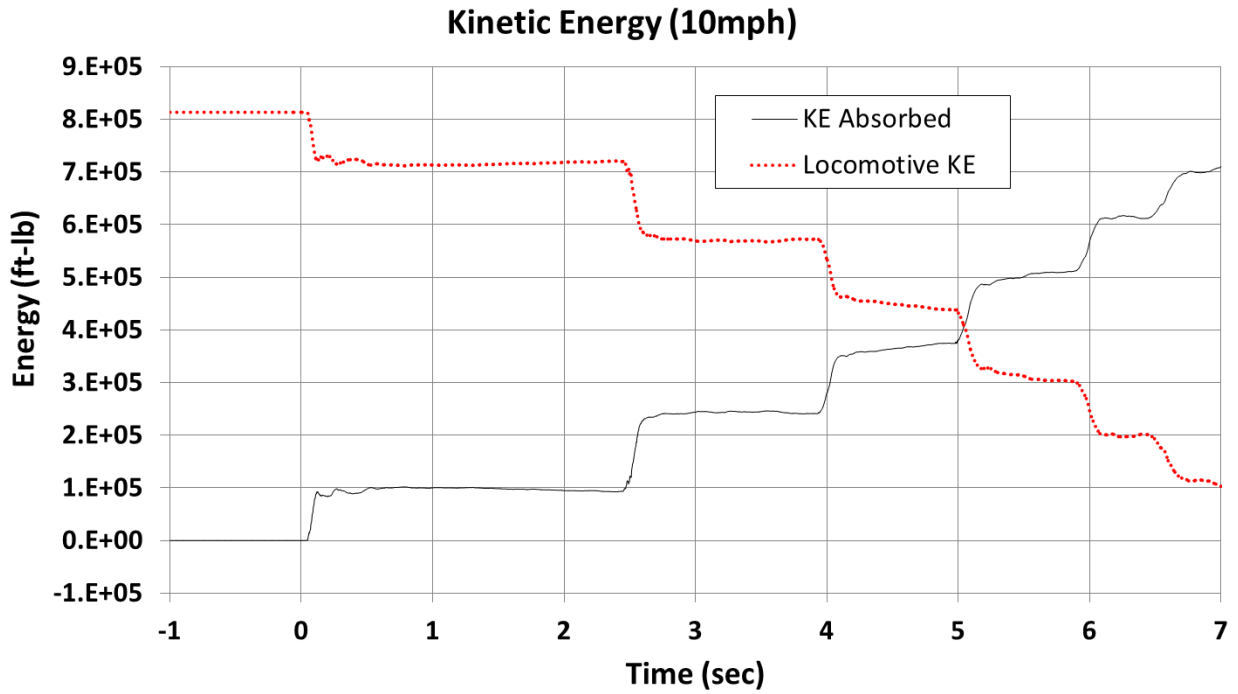


Figure 29. Impact Energy at 10 mph

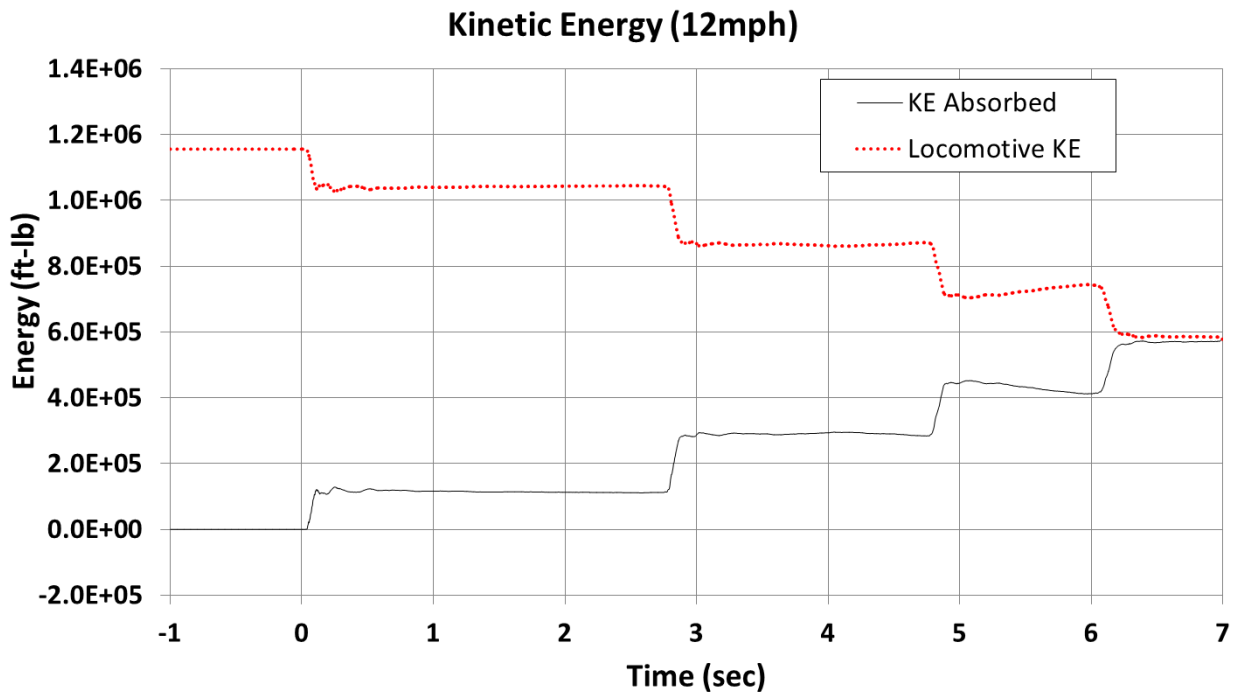


Figure 30. Impact Energy at 12 mph

The primary string potentiometer measurements measured the displacement of the M1 car coupler and the locomotive coupler. [Figure 31](#) and [Figure 32](#) show these displacements. For both the car and the locomotive, the coupler moving into the draft pocket is reported as a negative

displacement. These figures show that for most of the test runs, the coupler on the M1 car showed much more displacement than the locomotive coupler. For example, at 8 mph the locomotive's coupler displaced approximately 0.8 inch into the draft pocket, while the car's coupler displaced approximately 1.6 inches. This shows that the locomotive's draft gear was stiffer than that of the M1 car. During the 10 mph and 12 mph test runs, the displacements did not exhibit the same behavior as during the lower speeds because the locomotive and car did not couple during these runs and impacted multiple times.

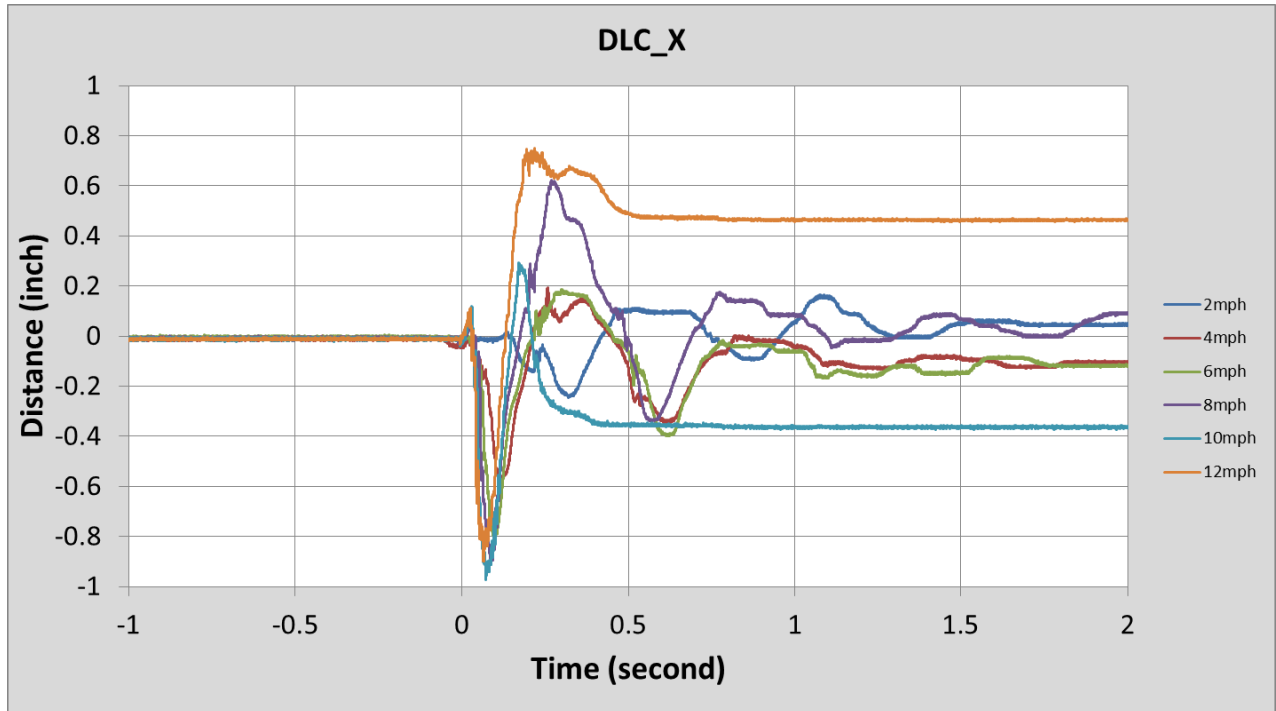


Figure 31. Locomotive Coupler Displacements

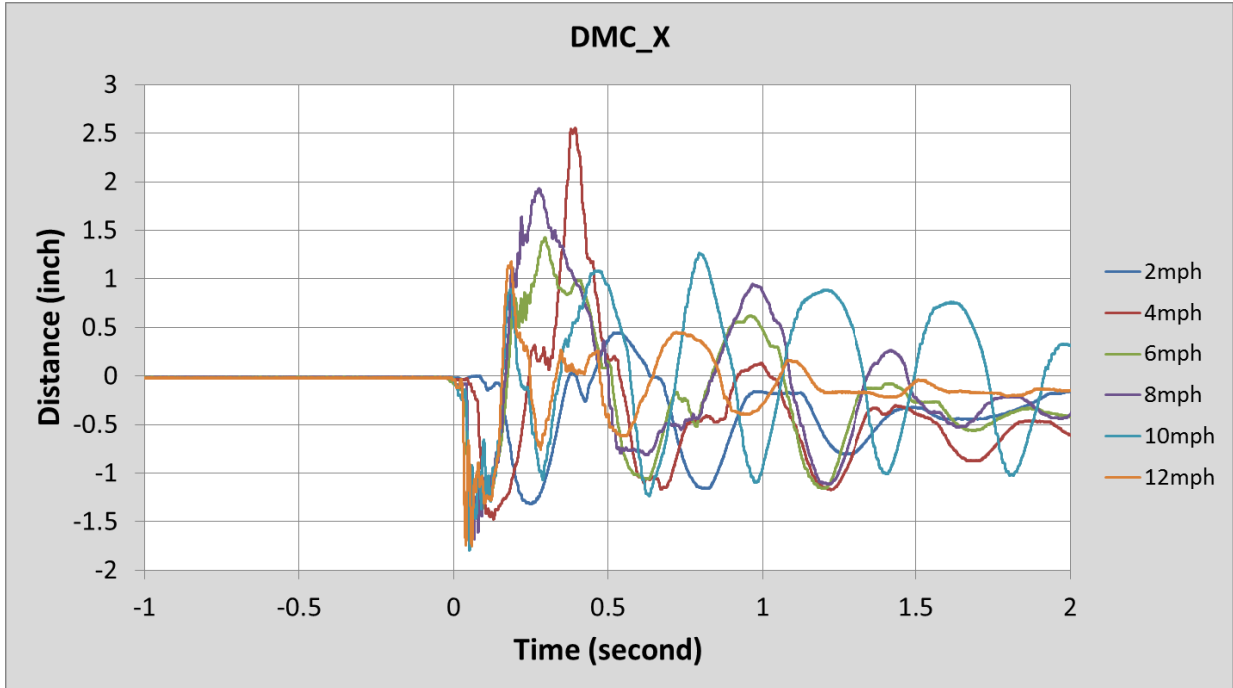


Figure 32. M1 Car Coupler Displacements

3.4 Summary of Post-Test Damage

The 1-inch diameter solid steel rods, which replaced the traction bars, buckled after the second test and were replaced with original traction bars taken from a different car.

The draft gear assembly in the M1 car consists of a series of rubber pads attached to metal plates; some plates were housed within the yoke and some were placed behind the yoke within the draft pocket. This assembly did sustain some damage during the test. [Figure 33](#) shows a plate within the yoke that was chipped along its outer edge. These plates were not accessible during testing and this chip was not discovered until the draft gear was removed from the M1 car. Thus, it is not known at which speed the plates were chipped.



Figure 33. Chipped Draft Plate

The plates in the draft assembly that were placed behind the yoke were also damaged during the test. [Figure 34](#) shows several of these plates that became noticeably bent. During the test, these plates were not accessible, and it is unknown how the damage progressed during each test run.



Figure 34. Bent Draft Plates

The M1 car's draft pocket sustained damage during the test. The interior of the draft pocket contains two structural members that run longitudinally, along the length of the pocket. These members were slightly bent ([Figure 35](#) and [Figure 36](#)) compared to the pre-test inspection. The visual inspection indicated that this deformation began during the 10-mph run and increased during the 12-mph run.



Figure 35. Bent Draft Pocket Member (right)



Figure 36. Bent Draft Pocket Member (left)

The exterior of the draft pocket also shows a small bend. This bend can only be seen on the lower flange of the draft pocket exterior, which is located on the right side of the M1 car (Figure 37). This bend is similar in magnitude to the bends of the structural members on the interior of the draft pocket. As with the bent draft pocket members, this damage first appeared during the 10-mph test run and increased during the 12-mph run.

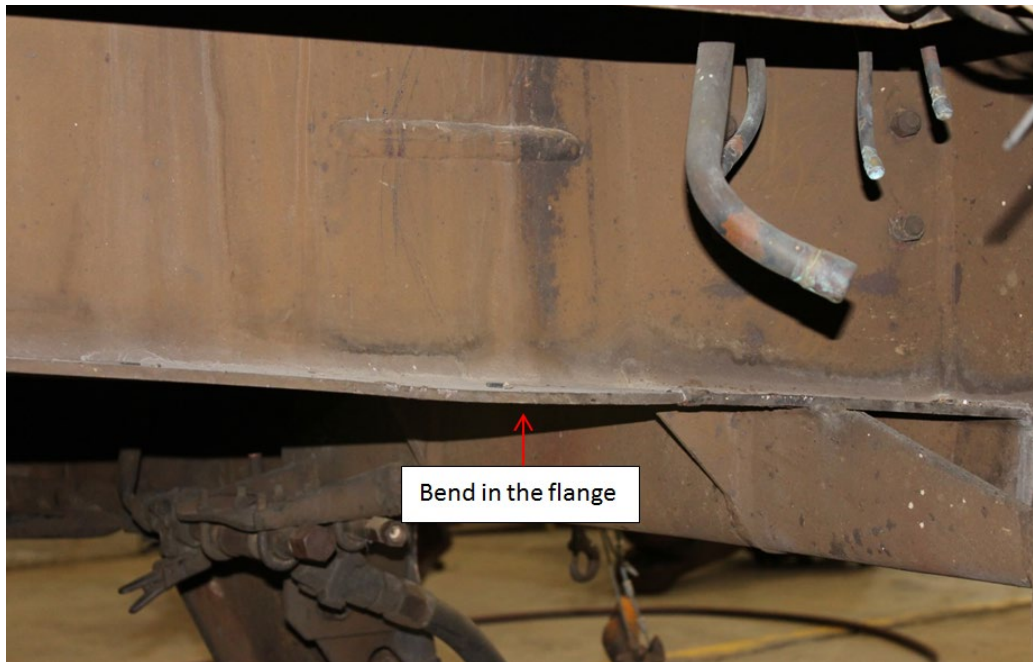


Figure 37. Exterior Bend in Draft Pocket, Right Side

One of the bump stops located at the opening of the draft pocket also received substantial damage (Figure 38). This stop was significantly impacted by the M1 coupler casting during the 10-mph impact and partially collapsed as a result.



Figure 38. Damaged Buff Stop

The coupler impact that damaged the bump stops also caused the draft pocket walls to bulge outward at the location of the bump stops. This damage occurred in the bellmouth of the draft pocket (Figure 39). This damage also occurred during the 10-mph test run.



Figure 39. Draft Pocket Side Wall Bulge

The M1 car's side sill sustained substantial damage during the test. The side sills are connected to the truck bolster via traction rods. During the impacts, the force that was transferred from the M1 car body to the trucks, through these rods, caused the side sills to buckle on the car's left side and crack on both sides. This buckling began during the 10-mph test run and continued during the 12-mph run, while the cracks appeared after the 12-mph test run. The car's left side sill is shown in [Figure 39](#). The right-side sill is shown in [Figure 40](#).



Figure 40. M1 Left Side Sill

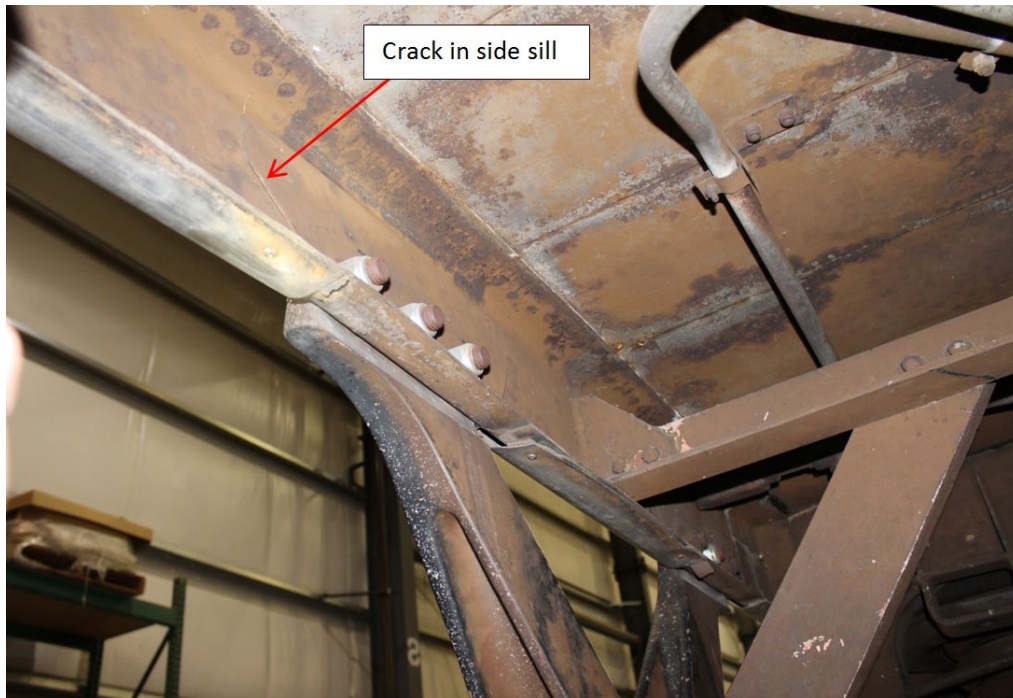


Figure 41. M1 Right Side Sill

The force that was transferred from the M1 car body to the trucks, through the traction rods also caused one of the traction rods to bend. The front left traction bar bent during the 8-mph run (Figure 42). This bend did not seem to increase during the subsequent runs (10 mph and 12 mph).



Figure 42. Bent Front Left Traction Bar

A structural member in the M1 car underframe also exhibited damage during the test (Figure 43). This lateral member on the right side of the car's underframe was bent during the 10-mph run.

This bend increased during the 12-mph run. This bent member is located near the buckled side sill on the right side of the car.



Figure 43. Bent Underframe Member

The belt loop on the front truck was severed during the test (Figure 44). This damage was observed after all test runs had been completed. Thus, it is unclear during when this damage occurred.



Figure 44. Severed Front Truck Belt Loop

In addition to the damage that was observed on the M1 car, the F40 locomotive sustained minor damage on its coupler. The coupler knuckle was chipped during a secondary impact on the 12-mph test run (Figure 45). This damage was minor, and did not affect the coupler's operability.



Figure 45. Chipped Locomotive Coupler

4. Conclusion

This report documents a series of impact tests between a passenger car and a locomotive, which were designed to establish a baseline maximum nondestructive coupling speed. The coupling speed will be used for comparison with future tests, where a locomotive will be modified with a push-back coupler and a deformable anti-climber.

TTCI conducted the impact tests, which were performed with a Budd M1 Car and a F40 locomotive, to evaluate the performance of both vehicles and provide data for future CEM tests. This impact testing was performed on November 18 and 19, 2015, at the TTC in Pueblo, CO.

The M1 car was impacted by the 245,800-pound locomotive in six impact tests at 1.89, 3.86, 5.67, 7.89, 9.95, and 11.86 mph, respectively. The car and locomotive failed to couple during the 9.95 mph and 11.86 mph impacts, but coupled successfully in all other test runs. The car and locomotive continued to move for various distances after each impact, which, due to the downhill grade on which the tests were conducted, added additional energy to the system after each impact had occurred. In the future, the stopping distance for each impact should be recorded to quantify the amount of energy added to the system after impact.

The most substantial test-related damage was inflicted upon the M1 car, with the F40 locomotive sustaining almost no noticeable damage. The M1 car sustained the maximum amount of damage during the 9.95 mph and 11.86 mph test runs. The draft pocket and draft gear on the M1 car showed deformation after these tests; however, the most significant damage was the buckling and cracking of the side sills. Damage occurred first in the weakest member on the force transfer path, which for the M1 car, was the attachment of a traction rod bar to the side sill.

5. References

1. SAE J211/1 Standard. 1995 (2007). "[Instrumentation for Impact Test – Part 1: Electronic Instrumentation](#)." SAE International: Warrendale, PA.

Abbreviations and Acronyms

Abbreviations & Acronyms

Definition

CEM	Crash Energy Management
FRA	Federal Railroad Administration
TTC	Transportation Technology Center (the site)
TTCI	Transportation Technology Center, Inc. (the company)

Appendix A. Target Positions



Figure A1. Target Positions for Locomotive

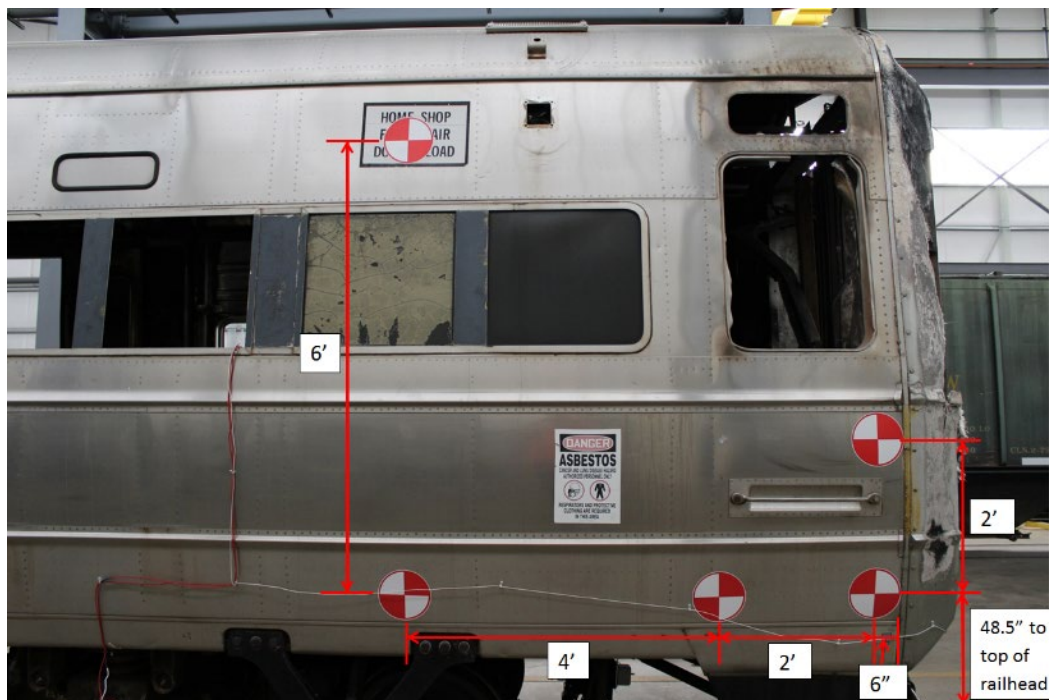


Figure A2. Target Positions for M1 Car

Appendix B. 2 mph Test Data

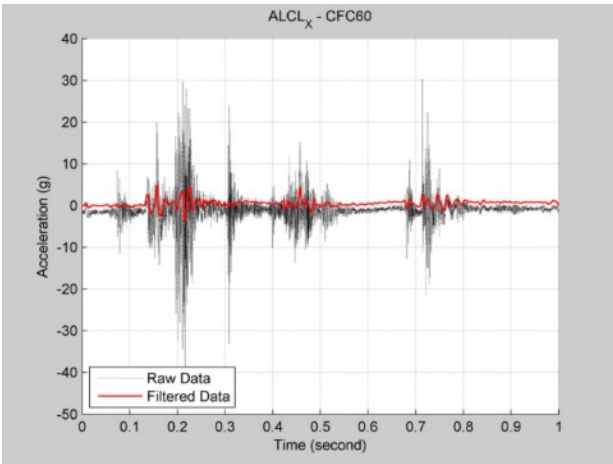


Figure B1. ALCL_X Accelerometer Data

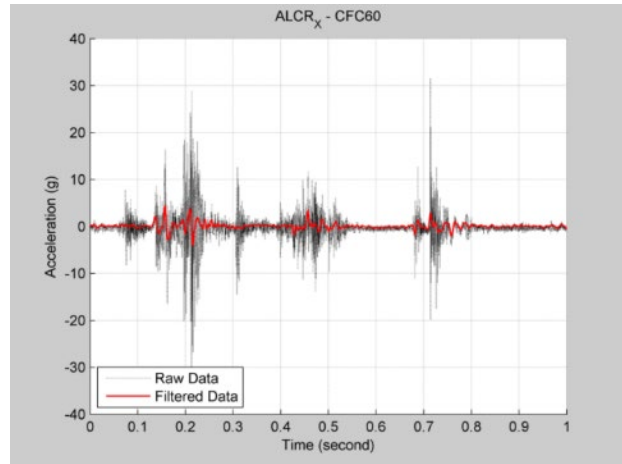


Figure B2. ALCR_X Accelerometer Data

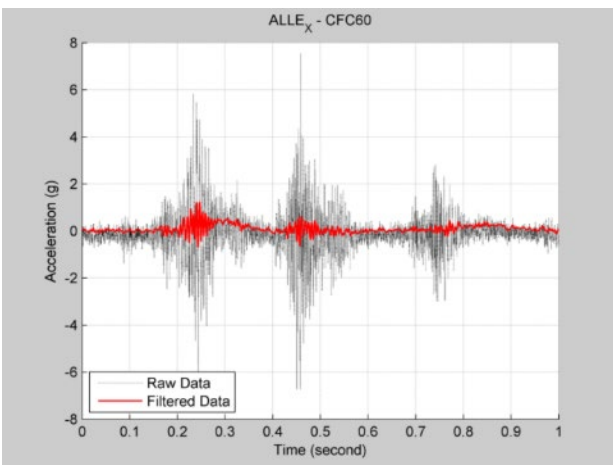


Figure B3. ALLE_X Accelerometer Data

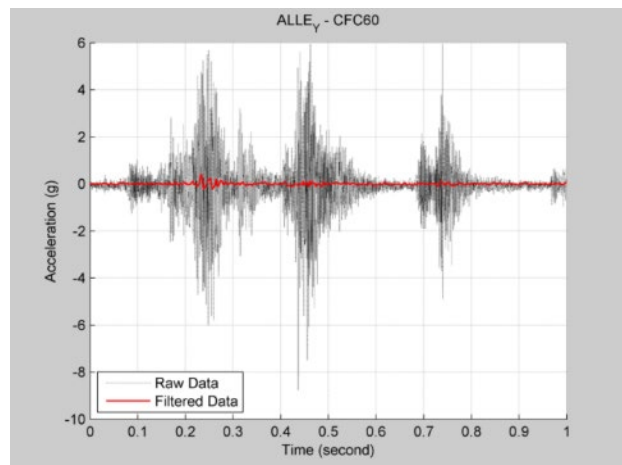


Figure B4. ALLE_Y Accelerometer Data

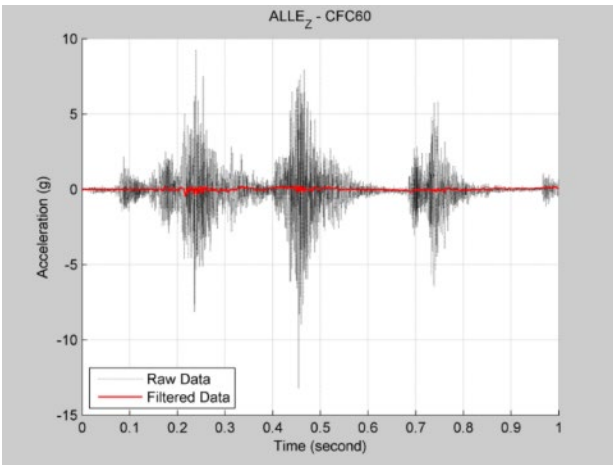


Figure B5. ALLE_Z Accelerometer Data

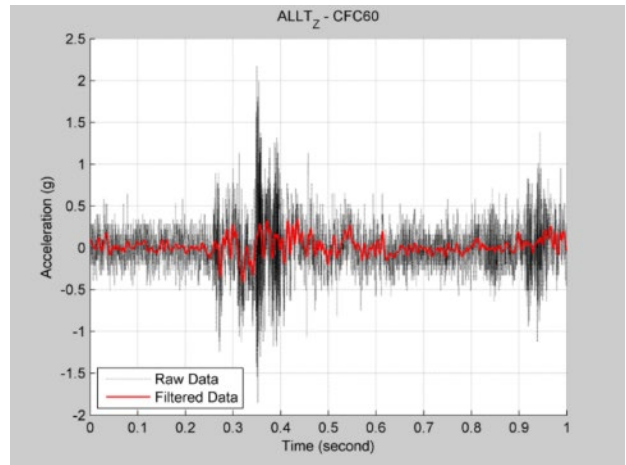


Figure B6. ALLT_Z Accelerometer Data

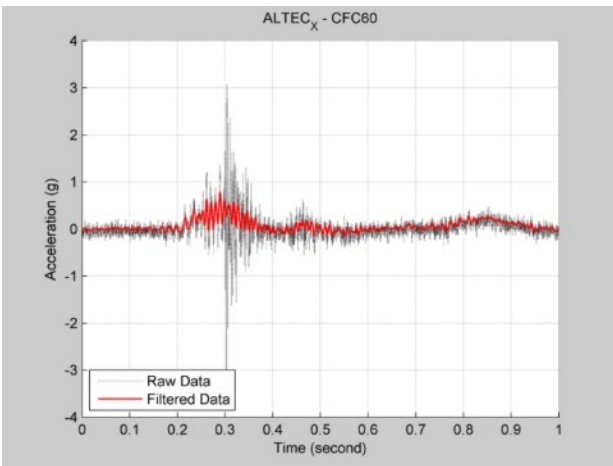


Figure B7. ALTEC_X Accelerometer Data

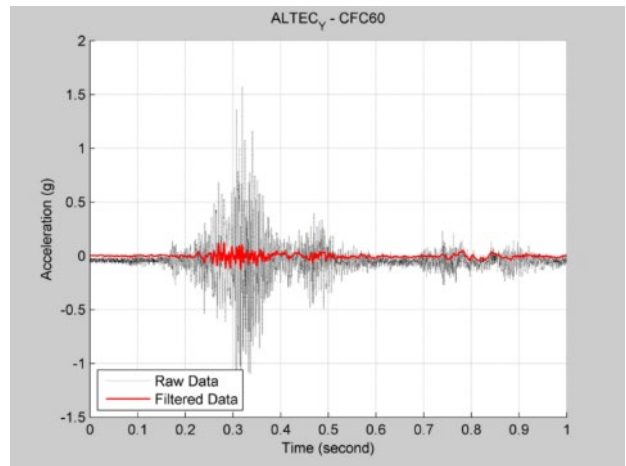


Figure B8. ALTEC_Y Accelerometer Data

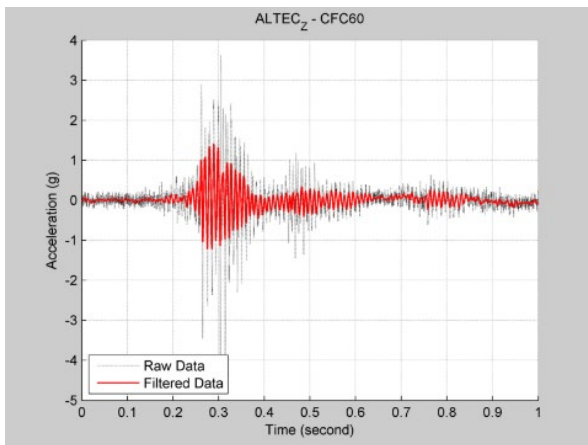


Figure B9. ALTEC_Z Accelerometer Data

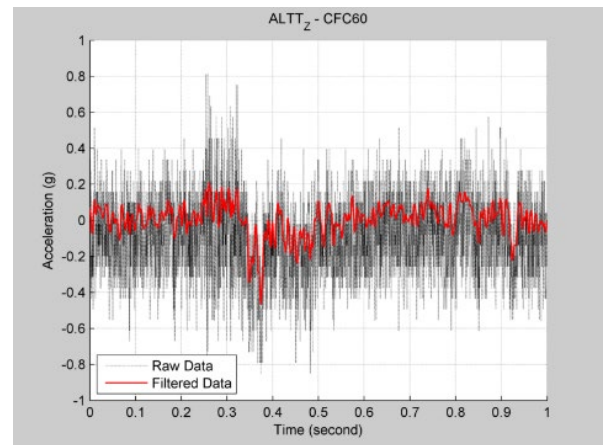


Figure B10. ALTT_Z Accelerometer Data

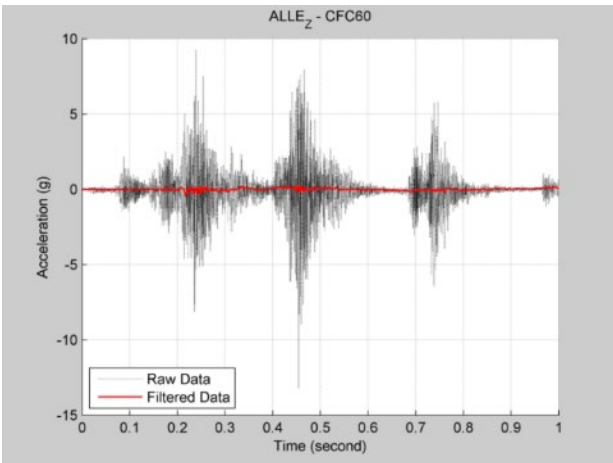


Figure B5. ALLE_Z Accelerometer Data

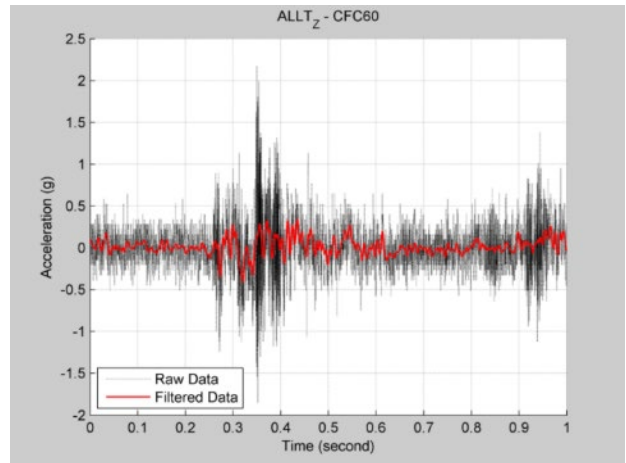


Figure B6. ALLT_Z Accelerometer Data

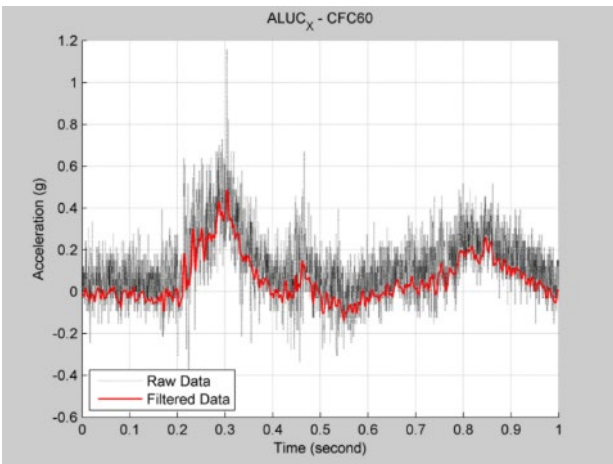


Figure B11. ALUC_X Accelerometer Data

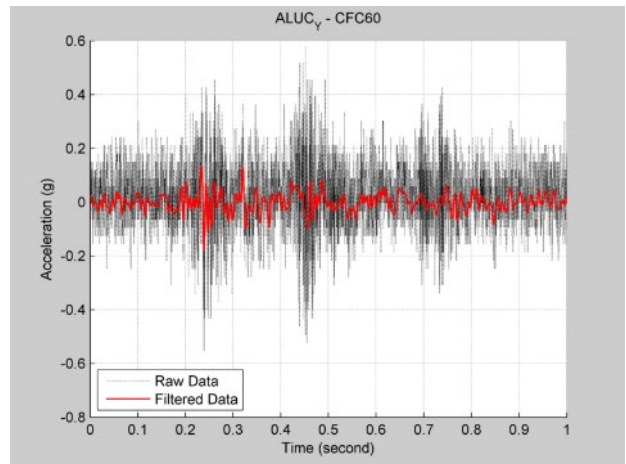
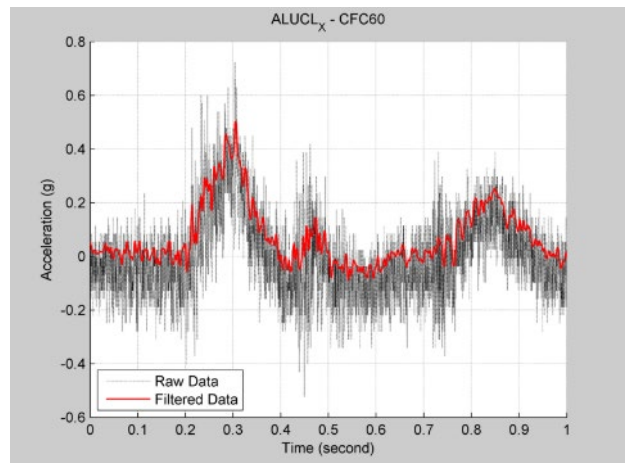
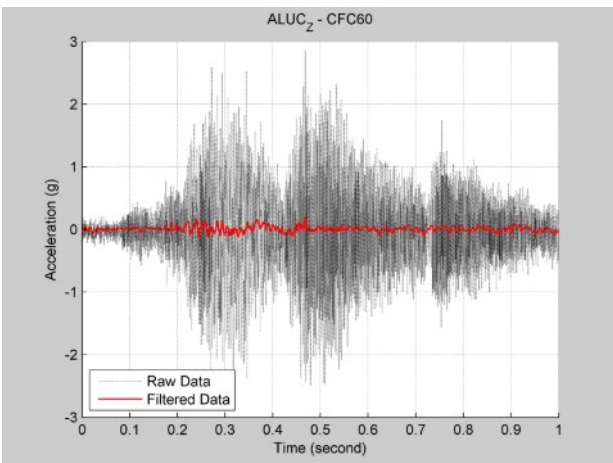


Figure B12. ALUC_Y Accelerometer Data



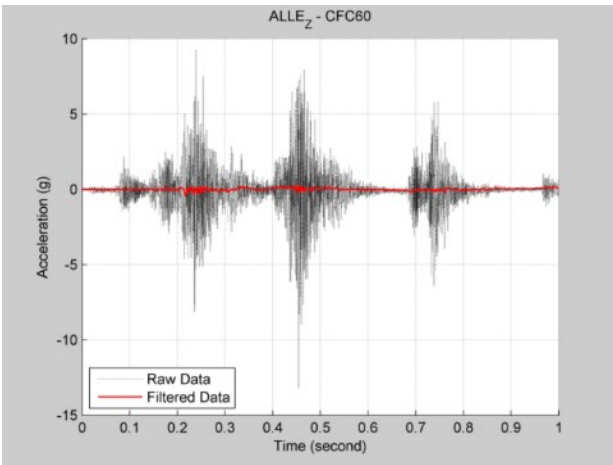


Figure B5. ALLE_Z Accelerometer Data

Figure B13. ALUC_Z Accelerometer Data

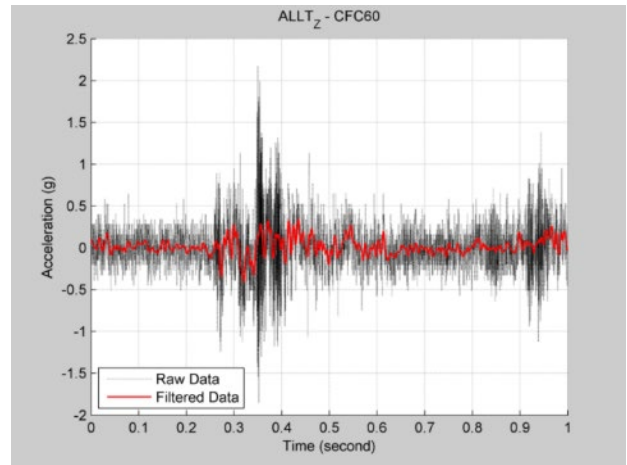


Figure B6. ALLT_Z Accelerometer Data

Figure B14. ALUCL_X Accelerometer Data

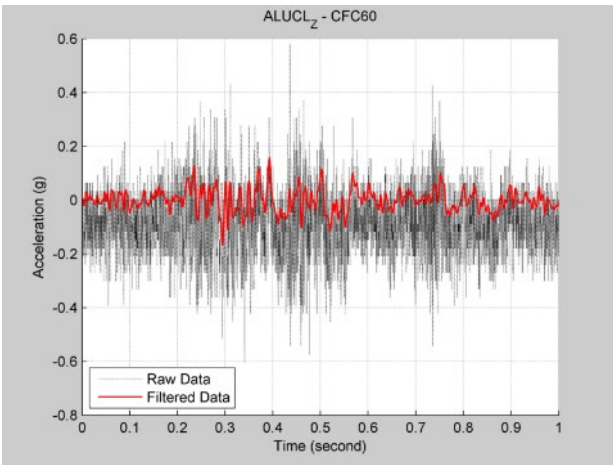


Figure B15. ALUCL_Z Accelerometer Data

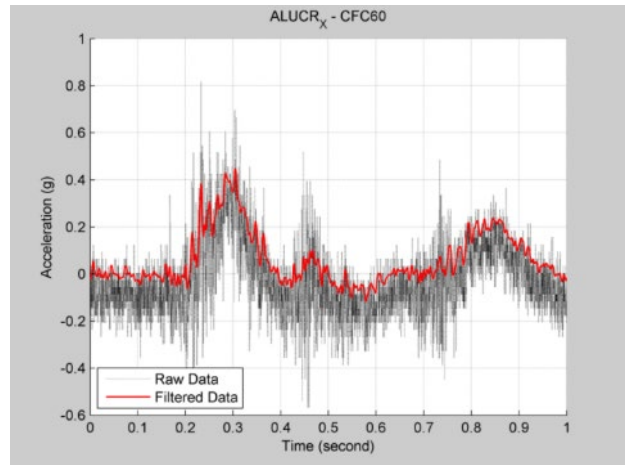


Figure B16. ALUCR_X Accelerometer Data

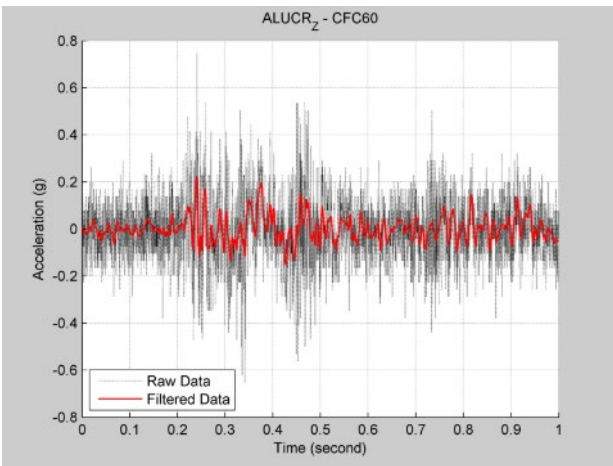


Figure B17. ALUCR_Z Accelerometer Data

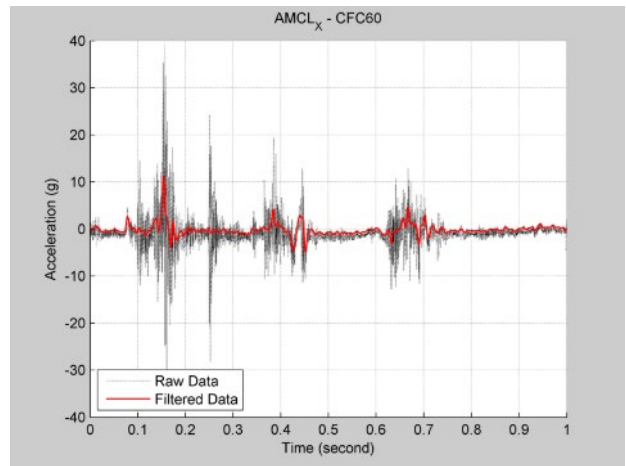


Figure B18. AMCL_X Accelerometer Data

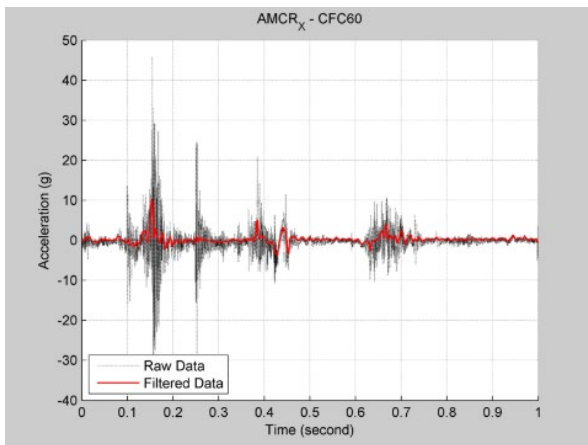


Figure B19. AMCR_X Accelerometer Data

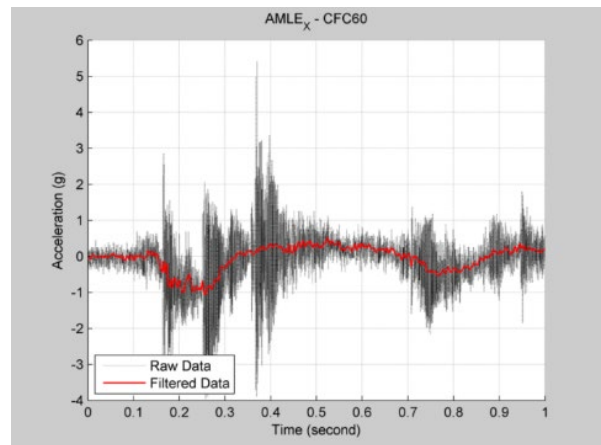


Figure B20. AMLE_X Accelerometer Data

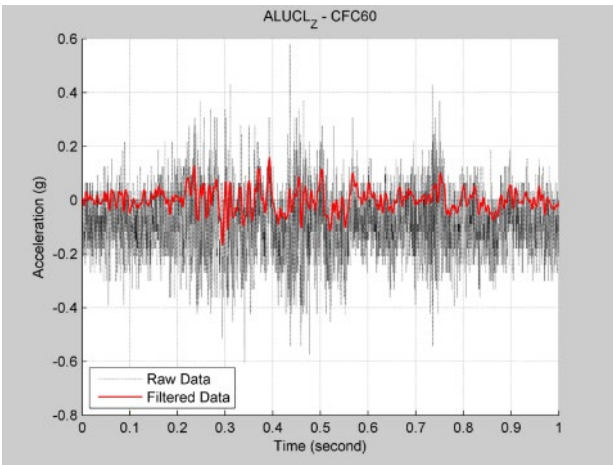


Figure B15. ALUCL_Z Accelerometer Data

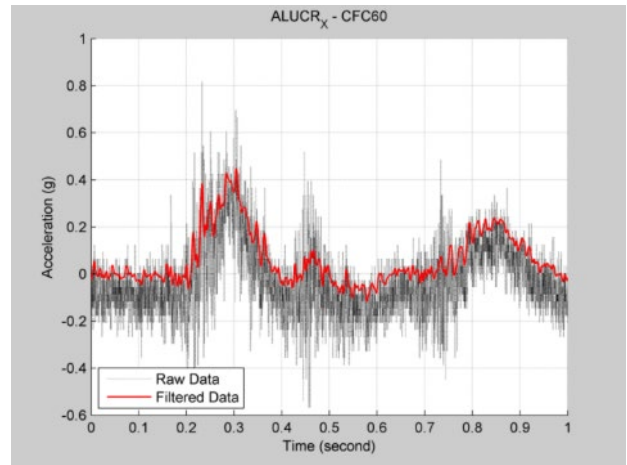


Figure B16. ALUCR_X Accelerometer Data

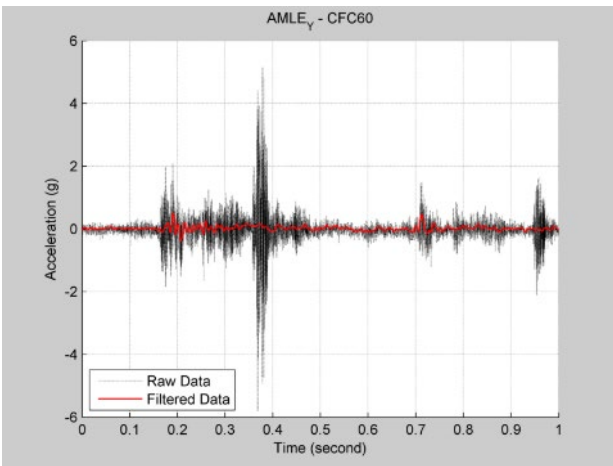


Figure B21. AMLE_Y Accelerometer Data

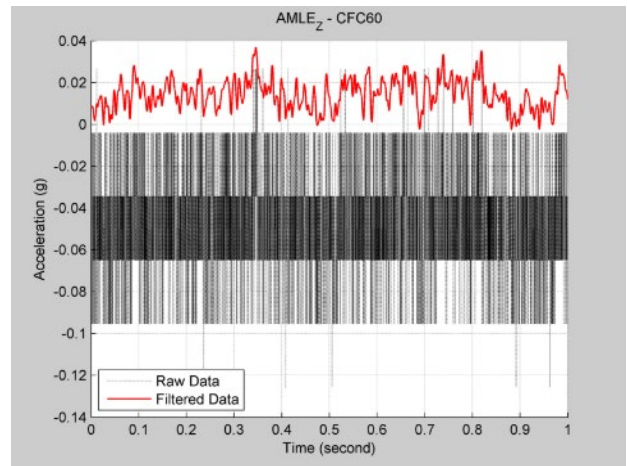


Figure B22. AMLE_Z Accelerometer Data

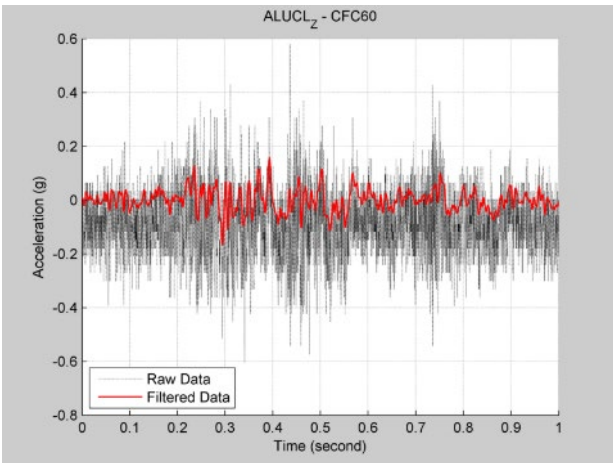


Figure B15. ALUCL_Z Accelerometer Data

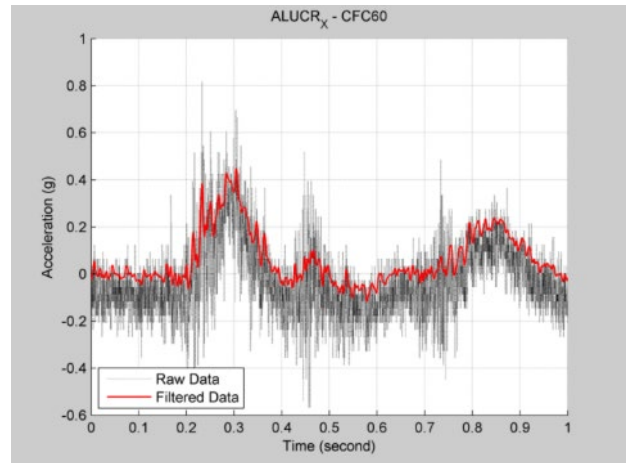


Figure B16. ALUCR_X Accelerometer Data

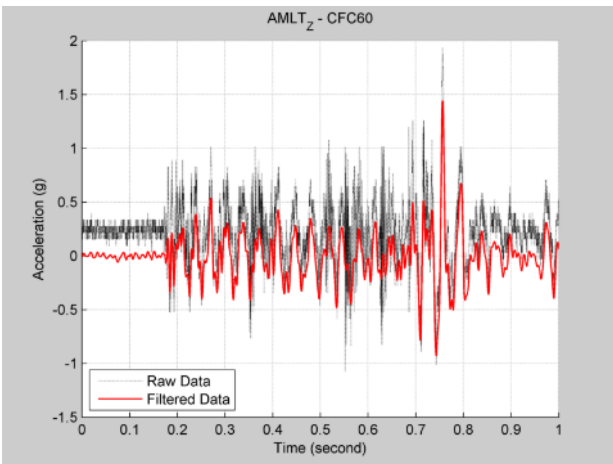


Figure B23. AMLT_Z Accelerometer Data

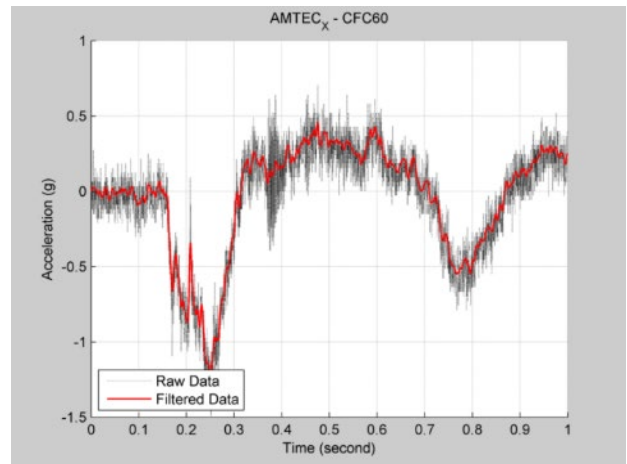


Figure B24. AMTEC_X Accelerometer Data

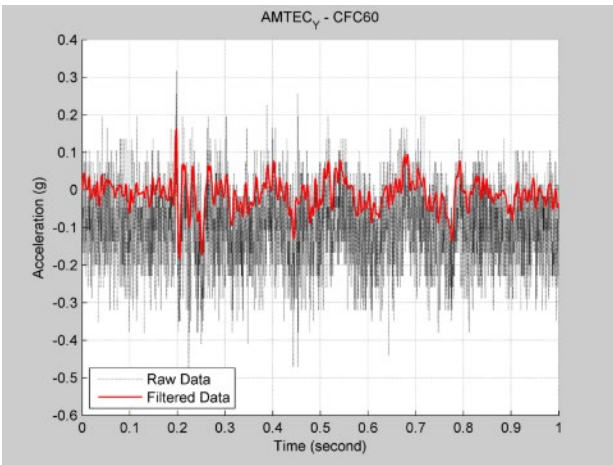


Figure B25. AMTEC_Y Accelerometer Data

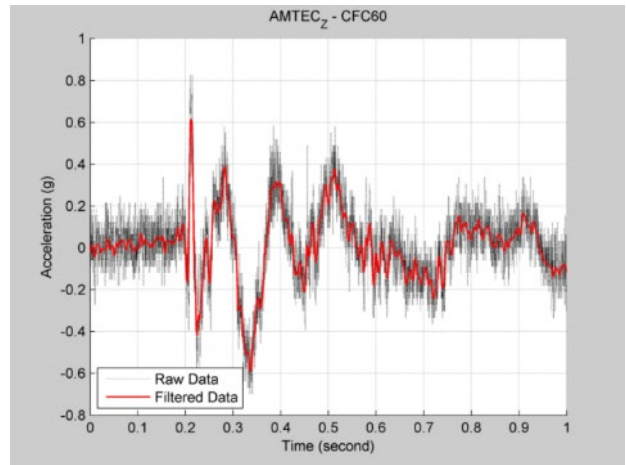


Figure B26. AMTEC_Z Accelerometer Data

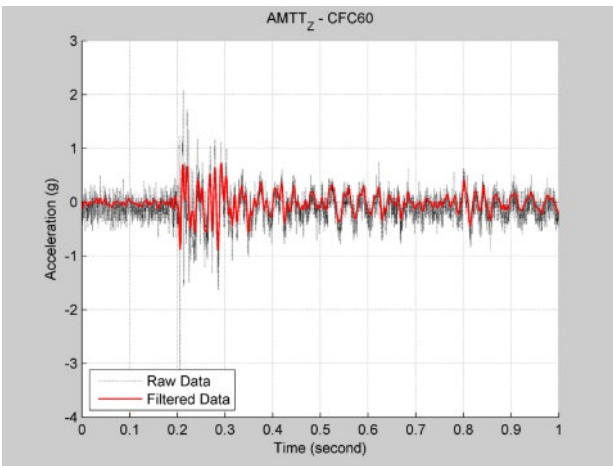


Figure B27. AMTT_Z Accelerometer Data

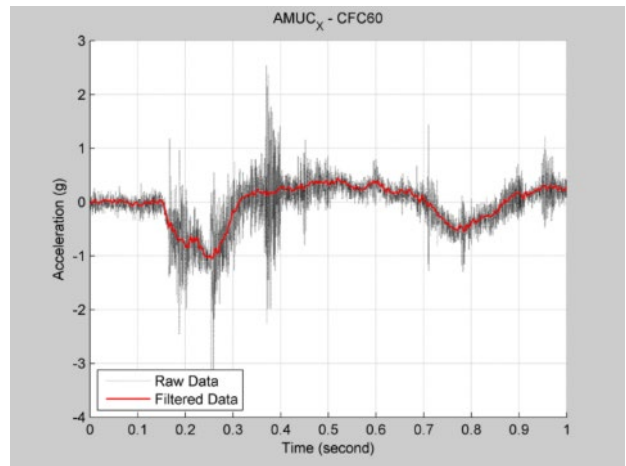


Figure B28. AMUC_X Accelerometer Data

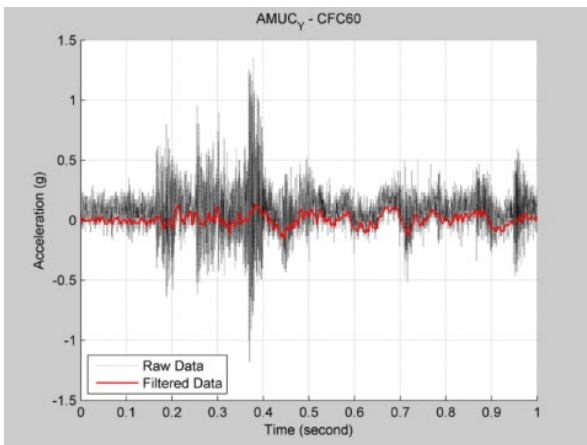


Figure B29. AMUC_Y Accelerometer Data

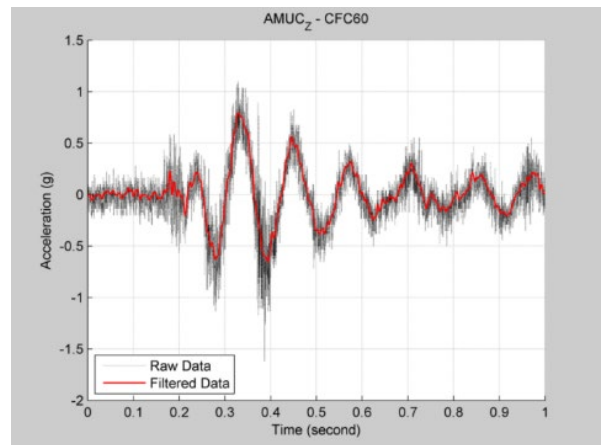


Figure B30. AMUC_Z Accelerometer Data

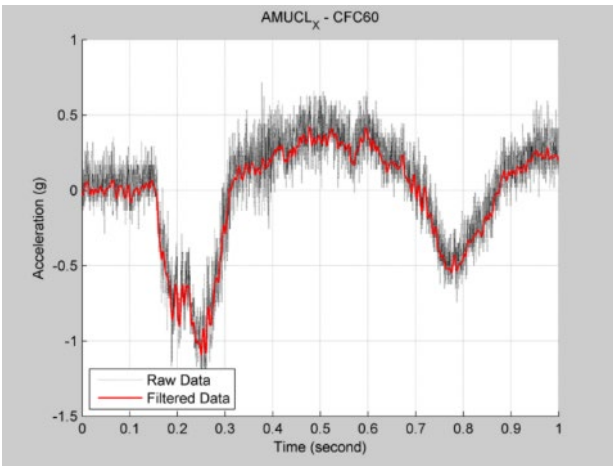


Figure B31. AMUCL_X Accelerometer Data

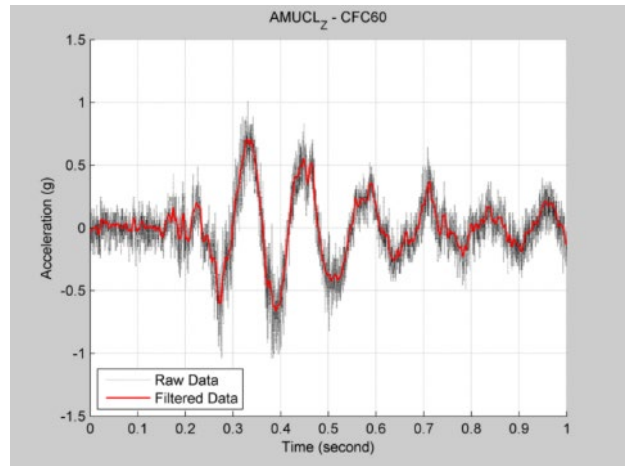


Figure B32. AMUCL_Z Accelerometer Data

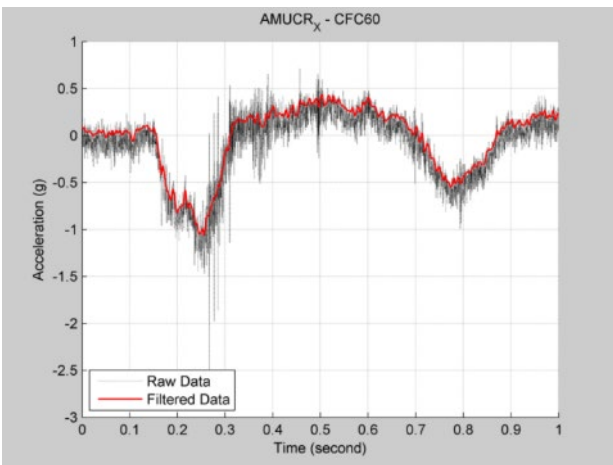


Figure B33. AMUCR_X Accelerometer Data

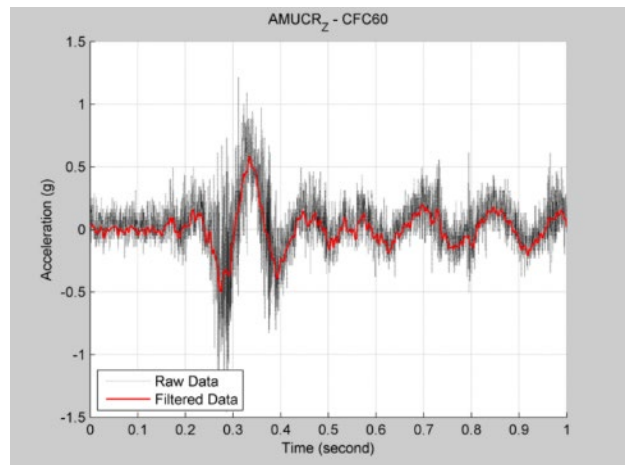


Figure B34. AMUCR_Z Accelerometer Data

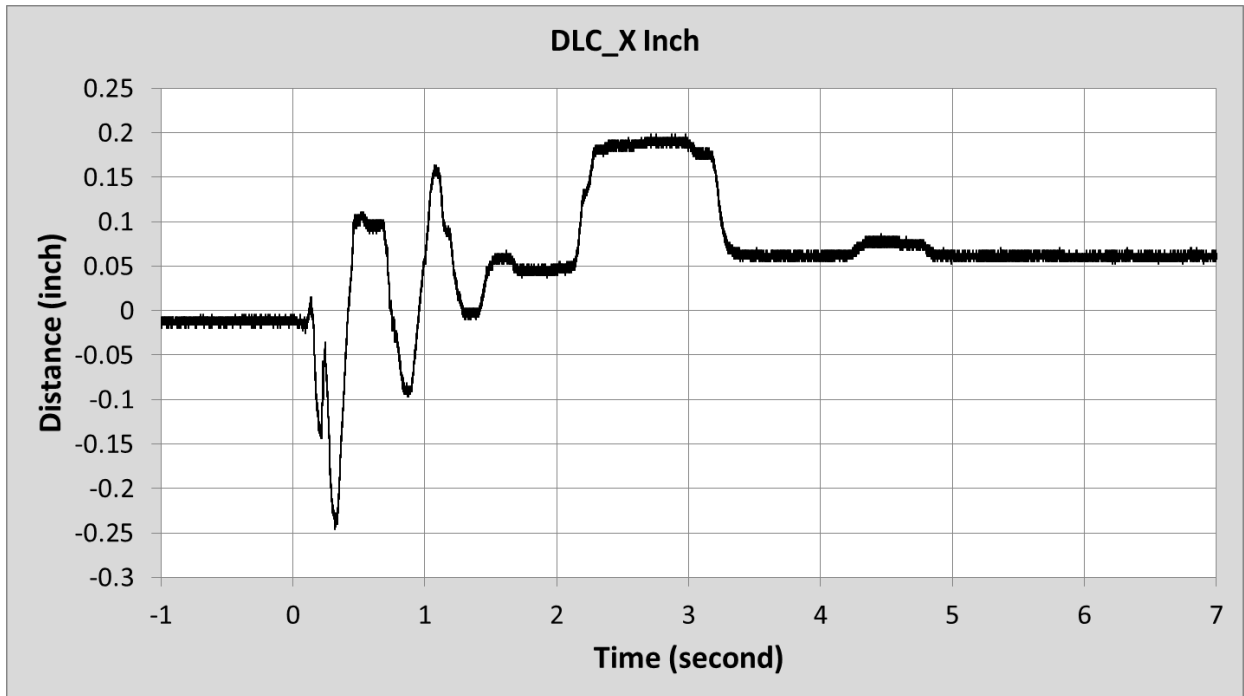


Figure B35. DLC_X String Potentiometer Data

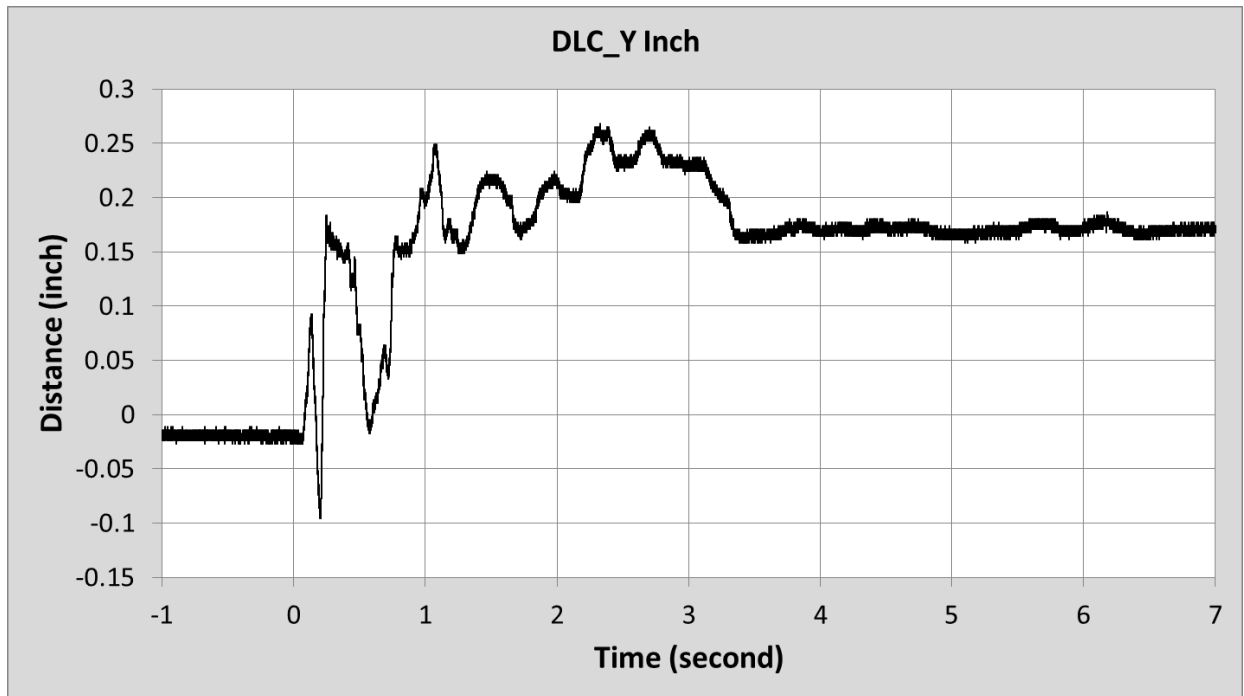


Figure B36. DLC_Y String Potentiometer Data

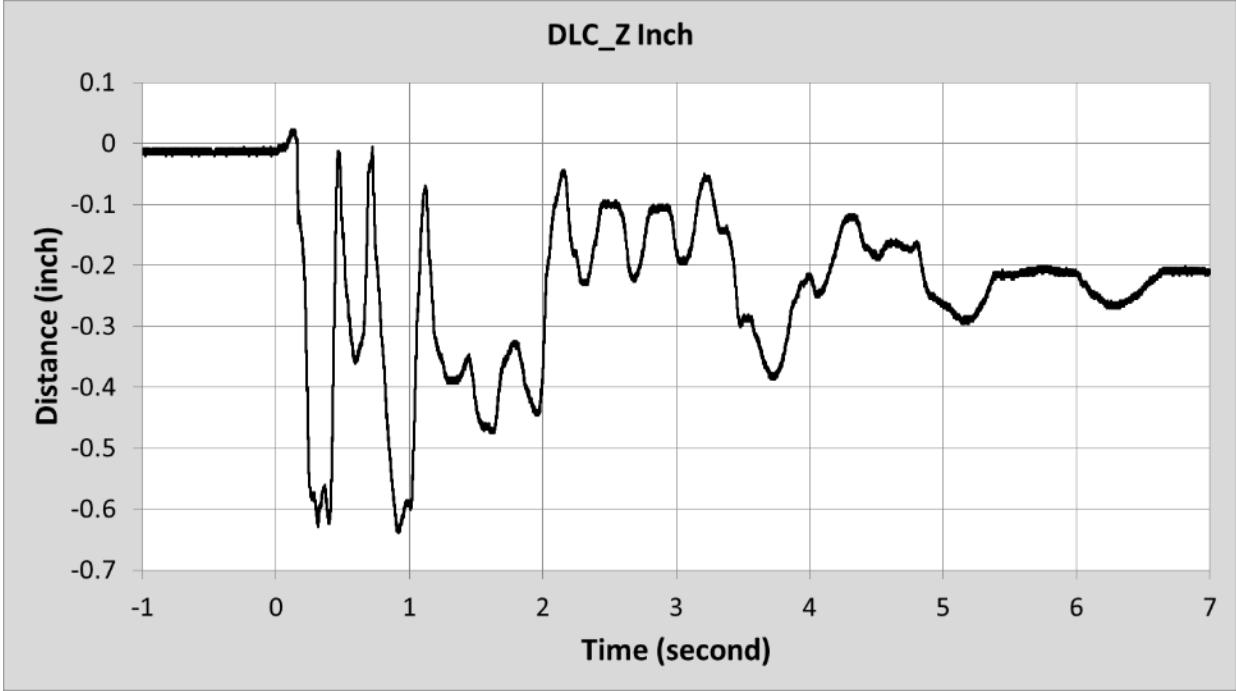


Figure B37. DLC_Z String Potentiometer Data

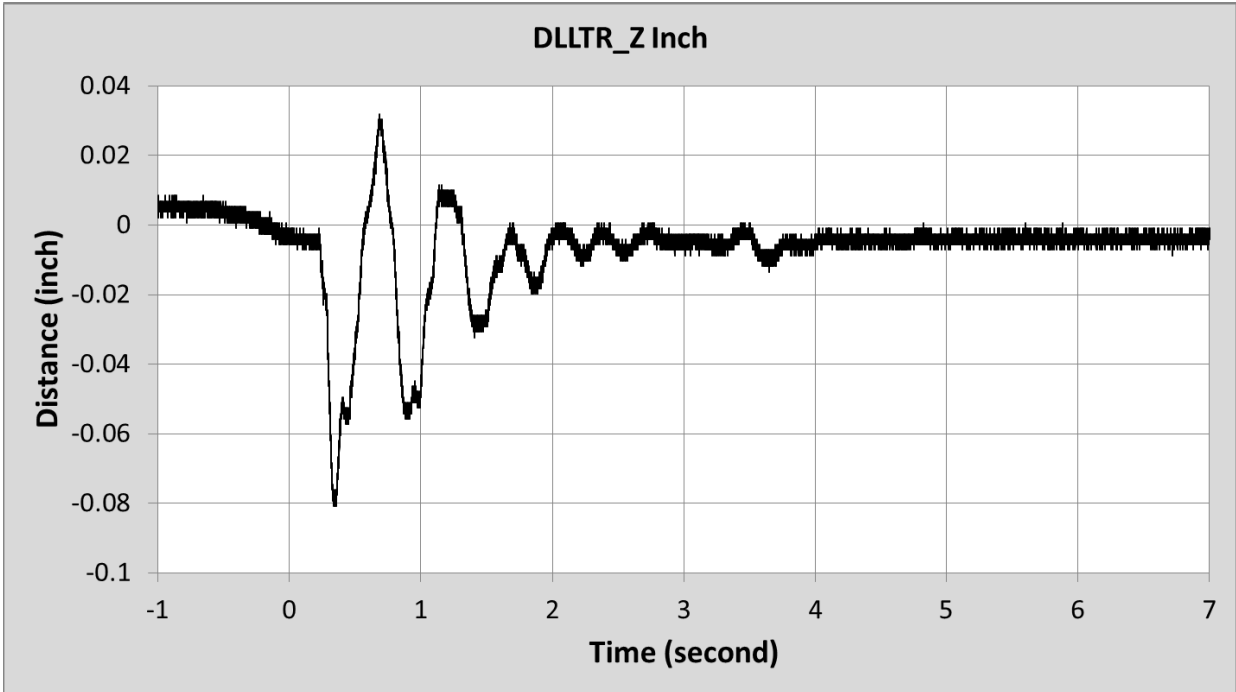


Figure B38. DLLTR_Z String Potentiometer Data

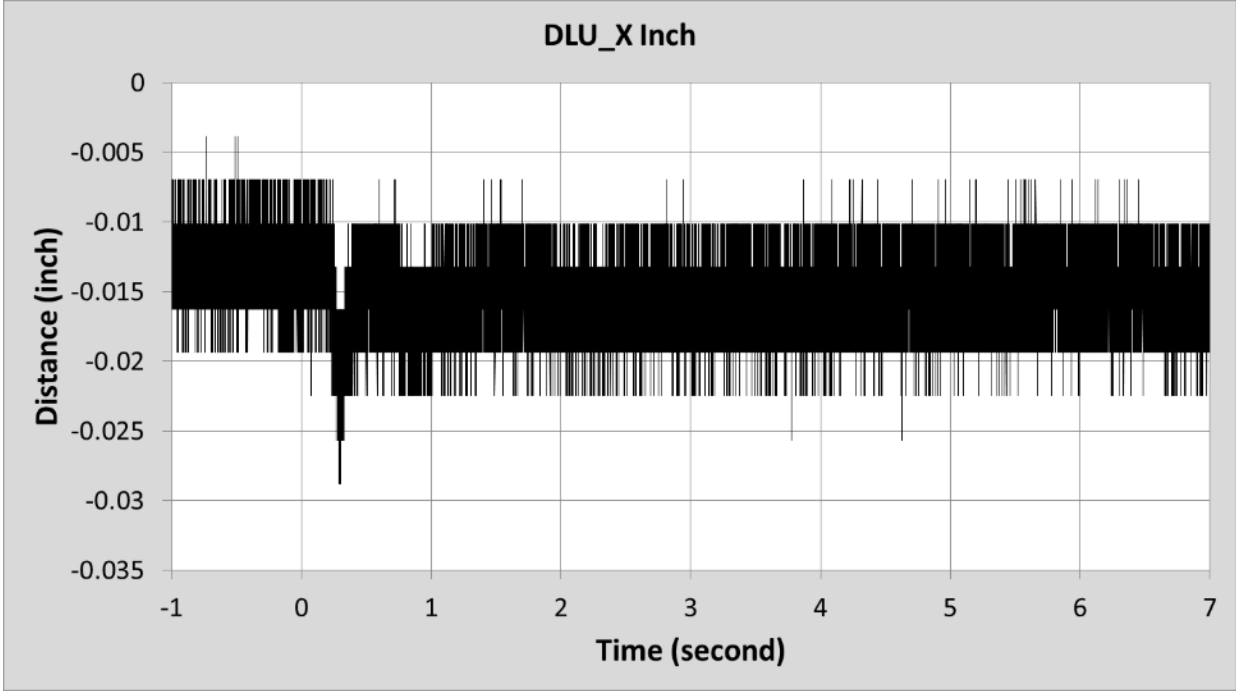


Figure B39. DLU_X String Potentiometer Data

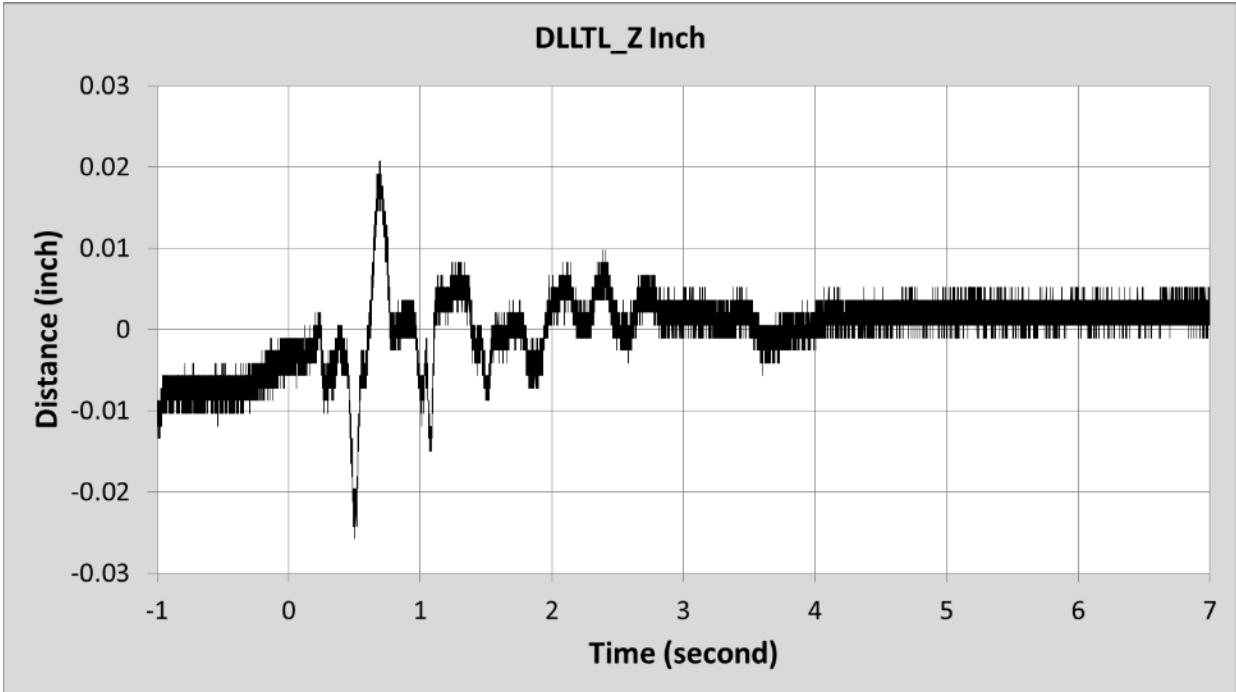


Figure B40. DLLTL_Z String Potentiometer Data

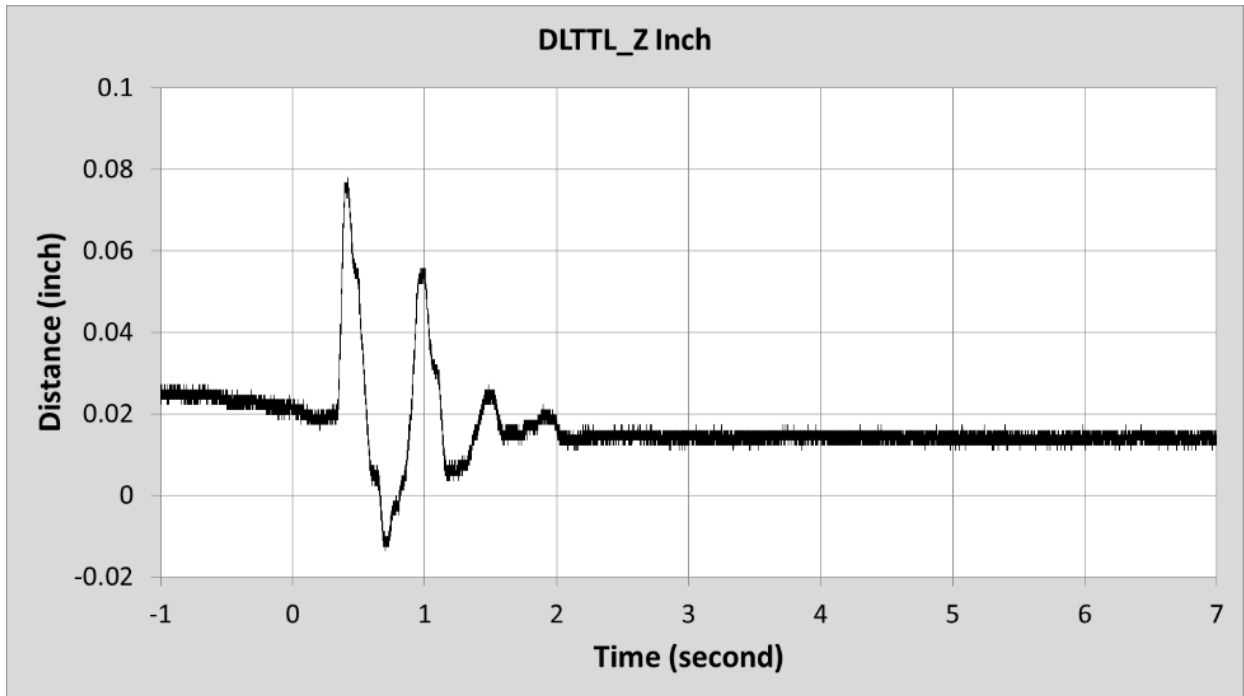


Figure B41. DLTTL_Z String Potentiometer Data

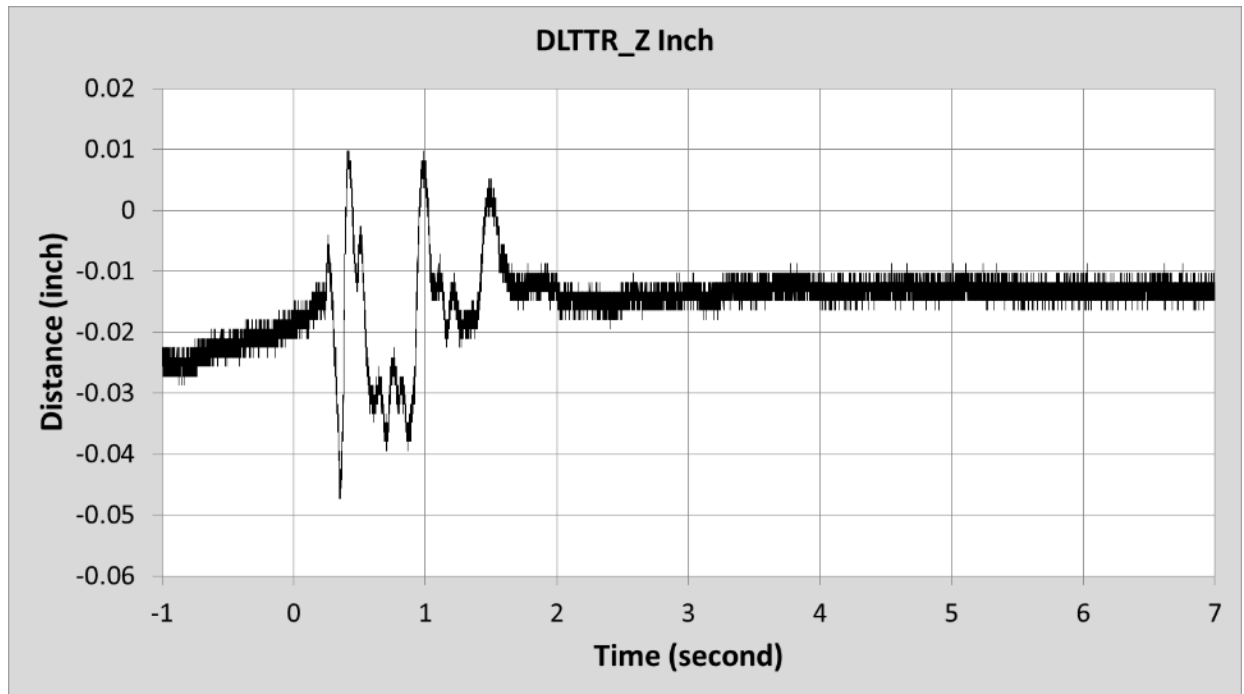


Figure B42. DLTTR_Z String Potentiometer Data

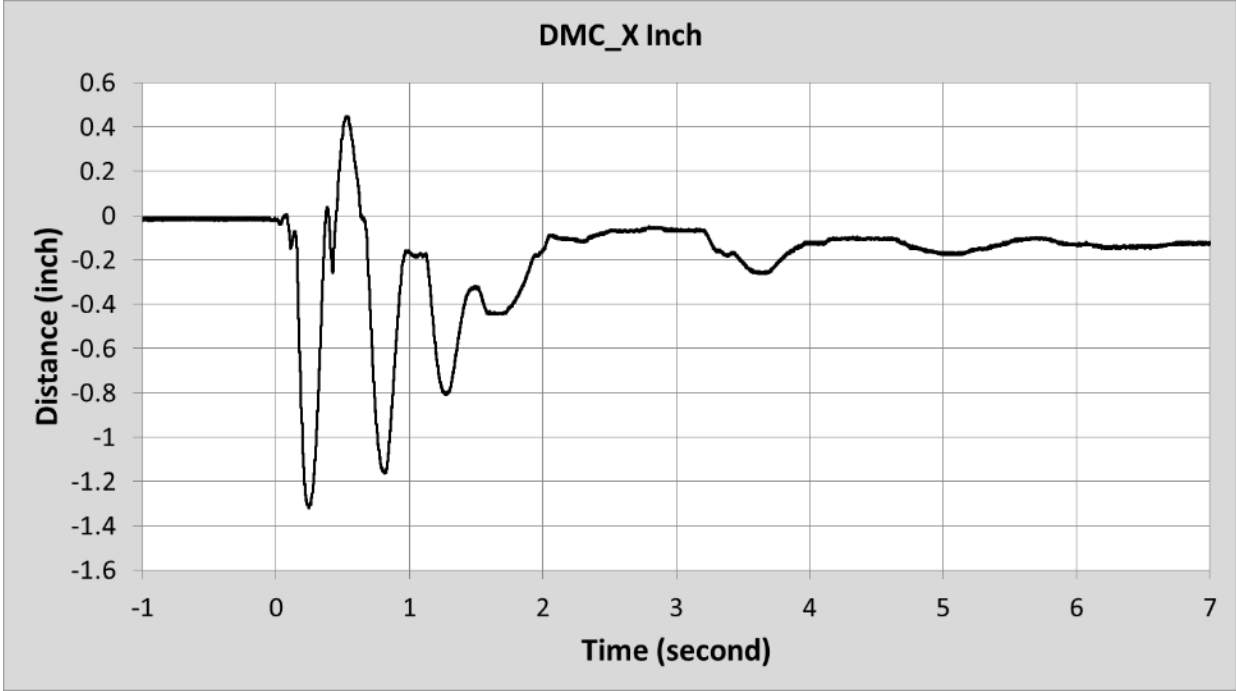


Figure B43. DMC_X String Potentiometer Data

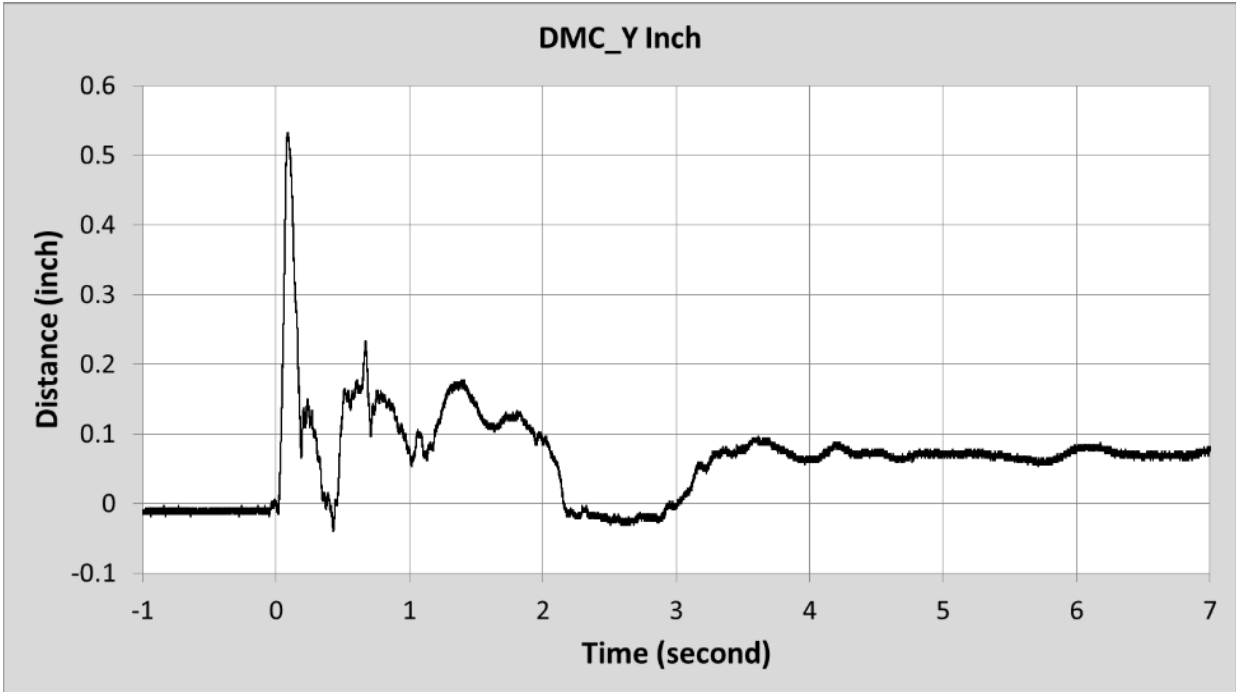


Figure B44. DMC_Y String Potentiometer Data

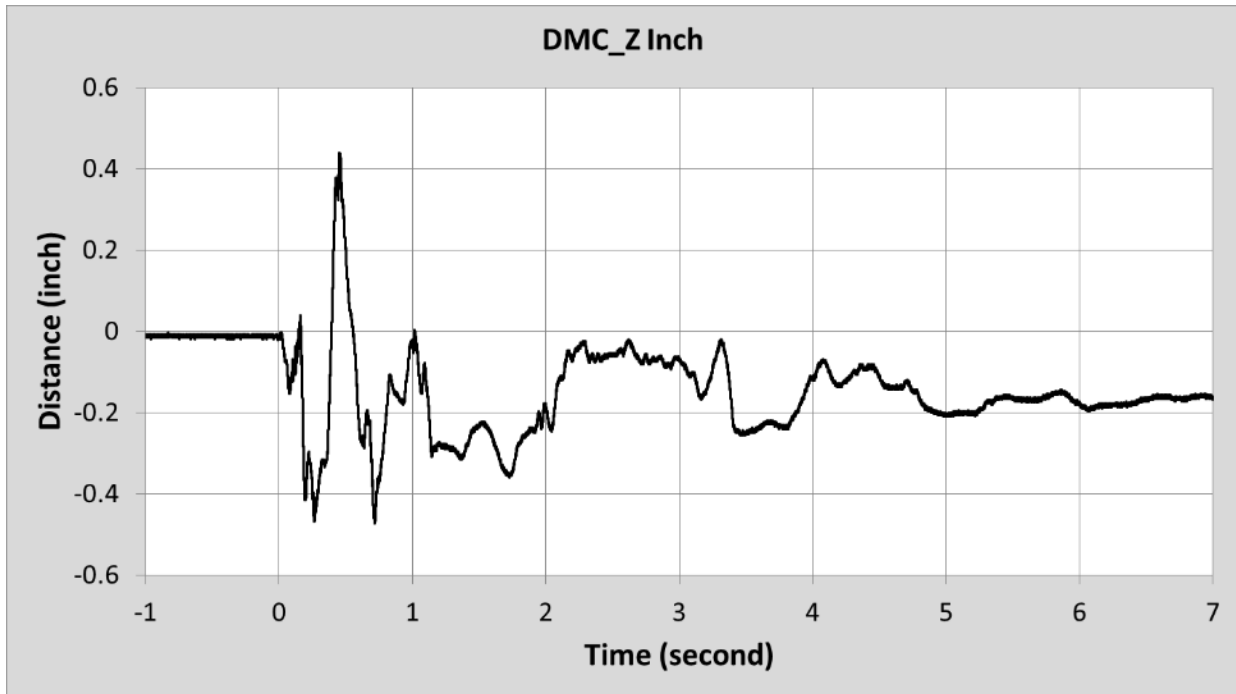


Figure B45. DMC_Z String Potentiometer Data

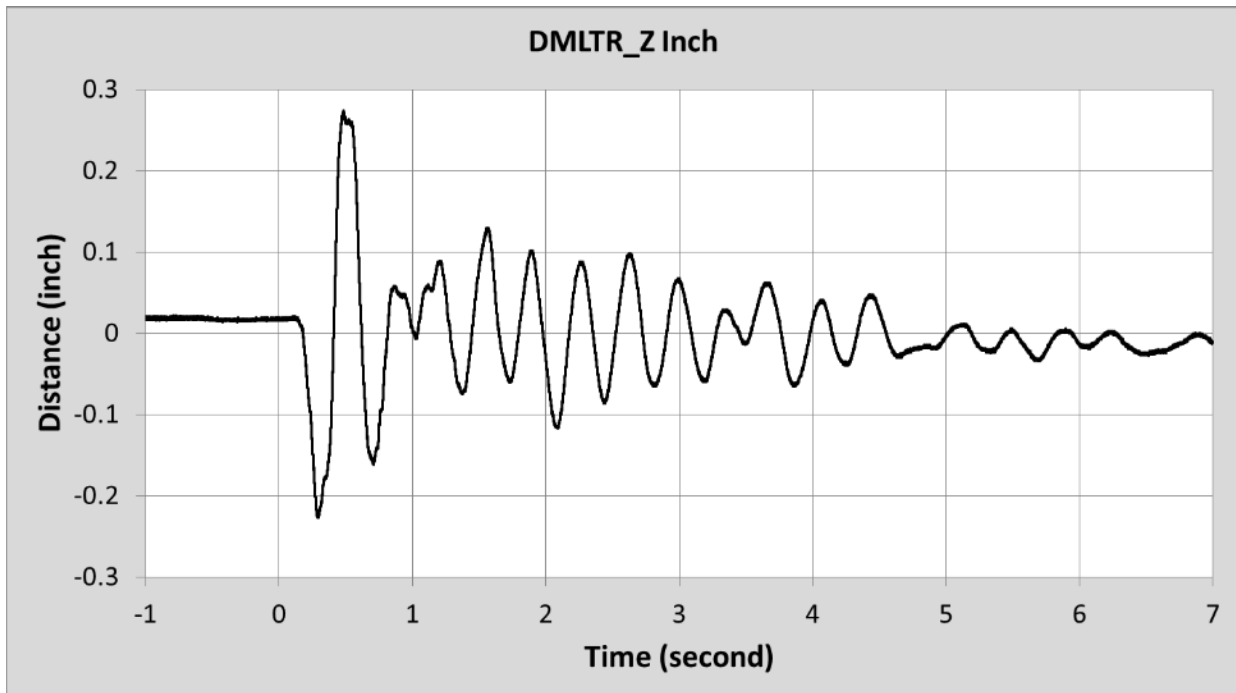


Figure B46. DMLTR_Z String Potentiometer Data

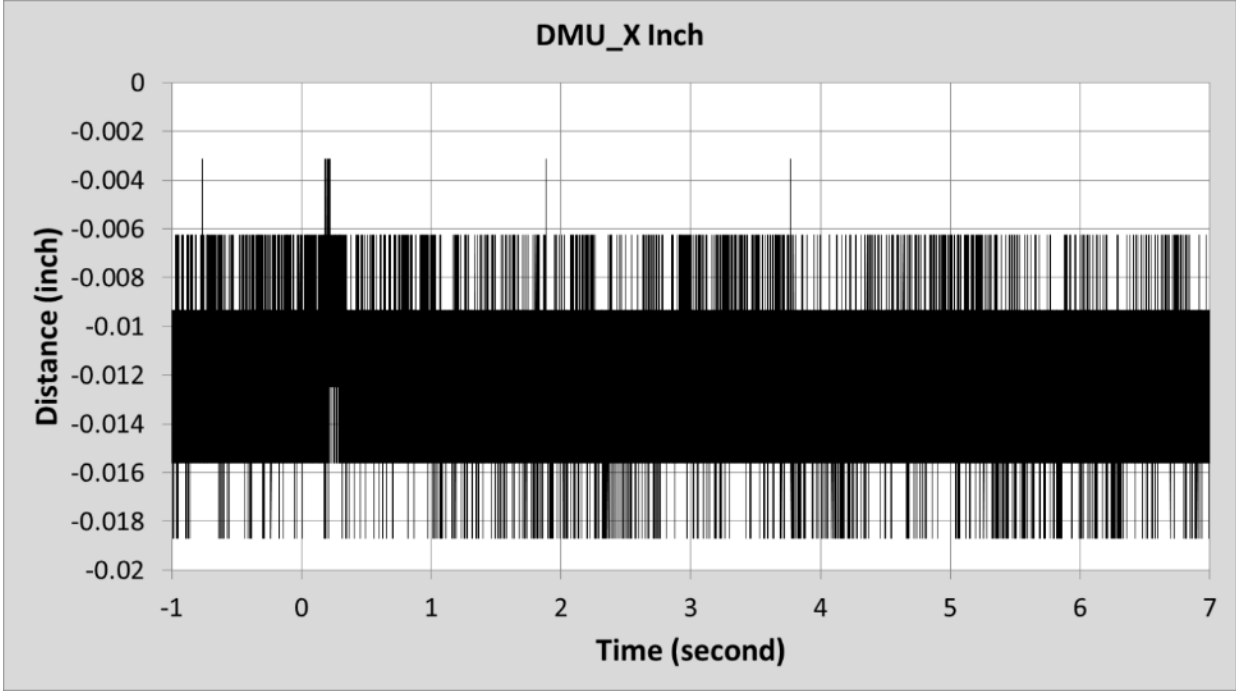


Figure B47. DMU_X String Potentiometer Data

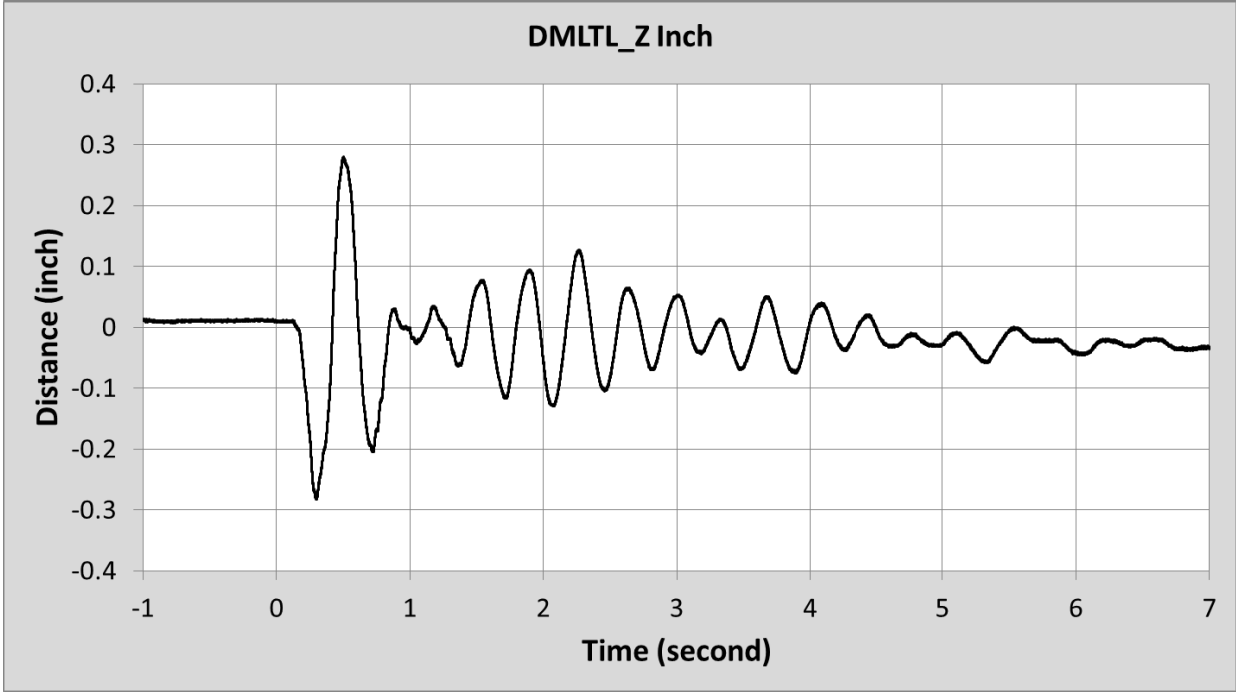


Figure B48. DMLTL_Z String Potentiometer Data

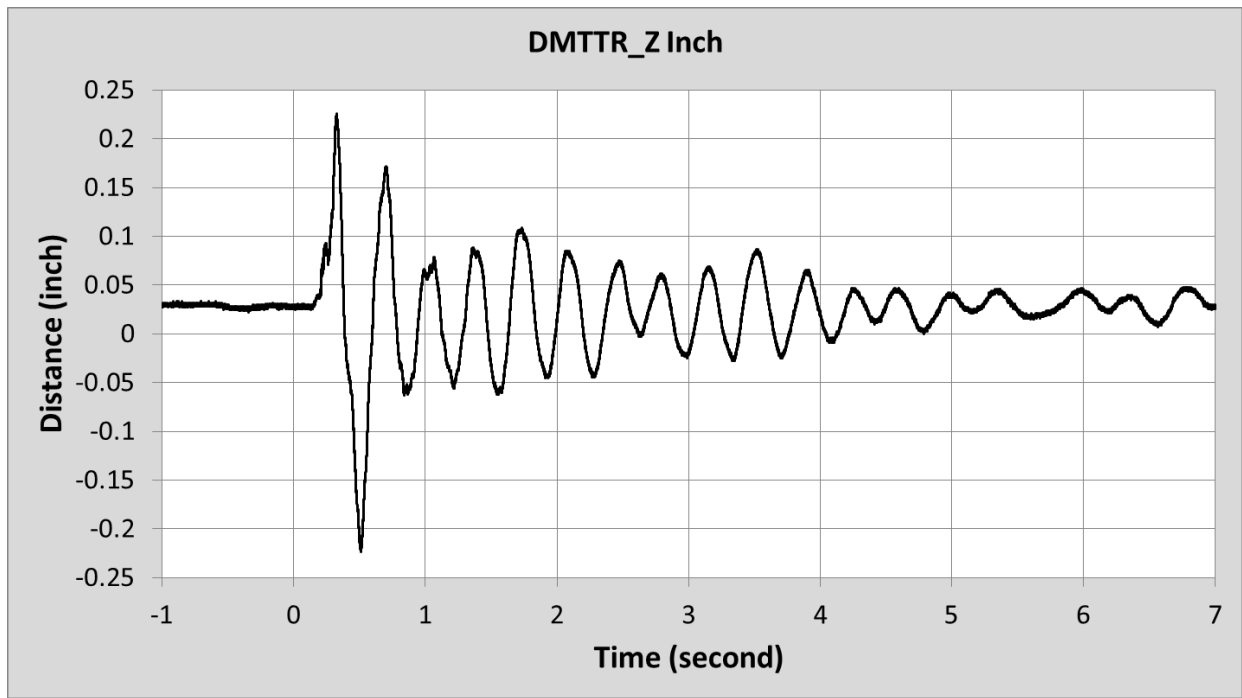


Figure B49. DMTTR_Z String Potentiometer Data

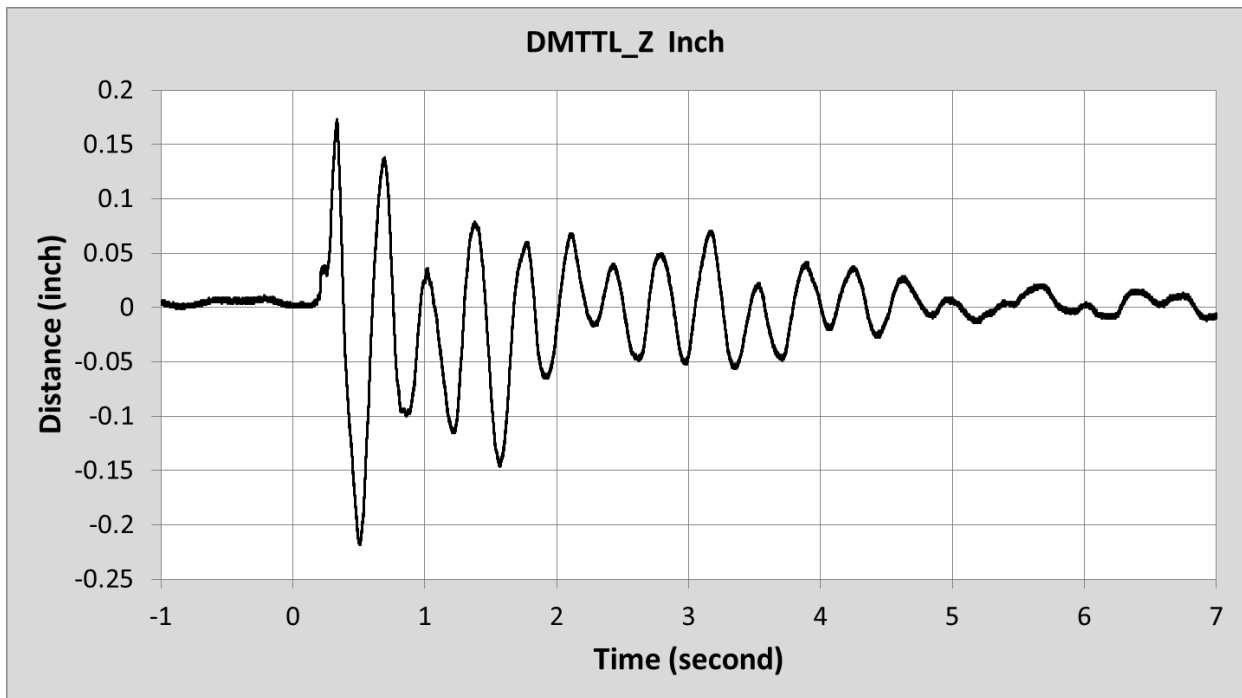


Figure B50. DMTTL_Z String Potentiometer Data

Appendix C. 4 mph Test Data

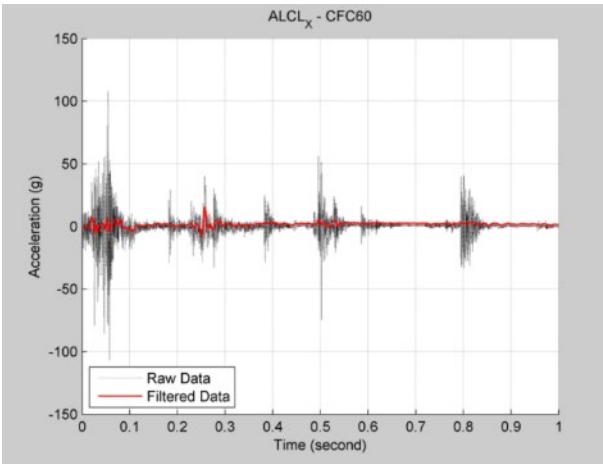


Figure C1. ALCL_X Accelerometer Data

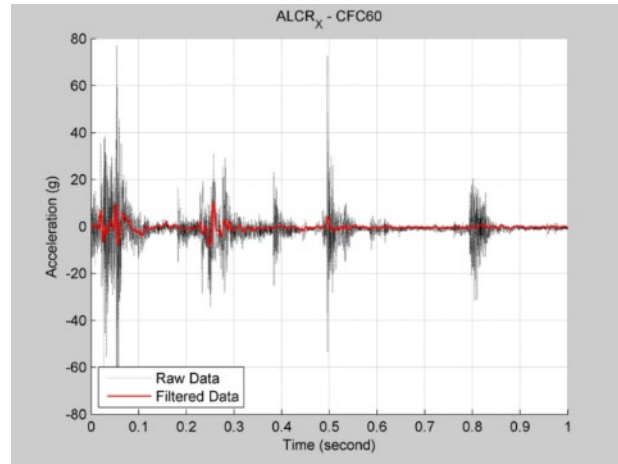


Figure C2. ALCR_X Accelerometer Data

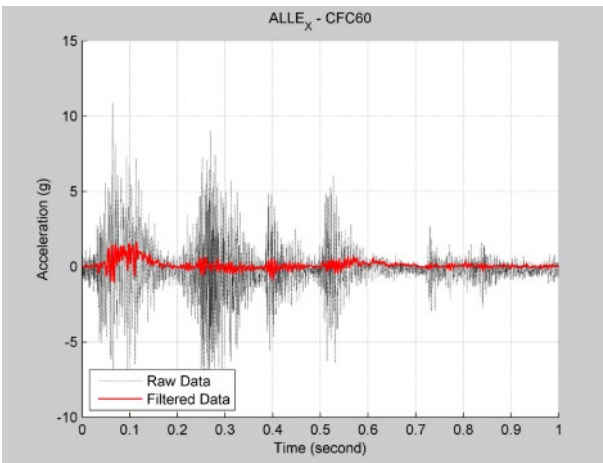


Figure C3. ALLE_X Accelerometer Data

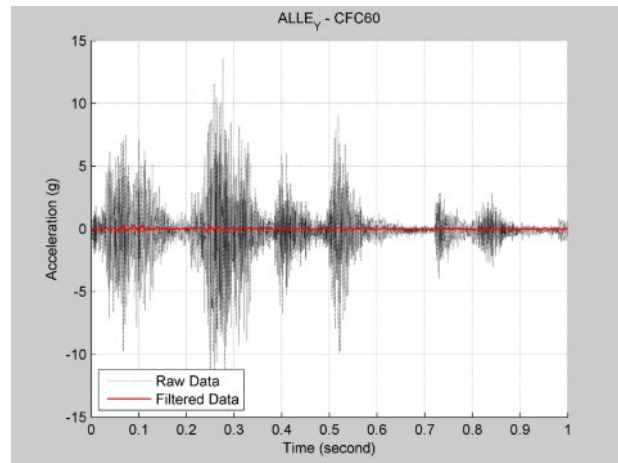


Figure C4. ALLE_Y Accelerometer Data

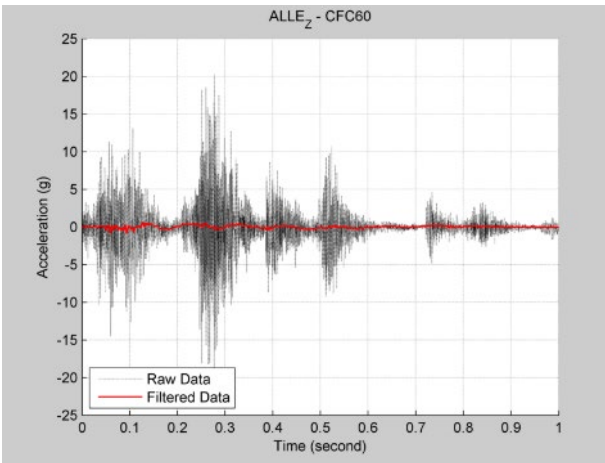


Figure C5. ALLE_Z Accelerometer Data

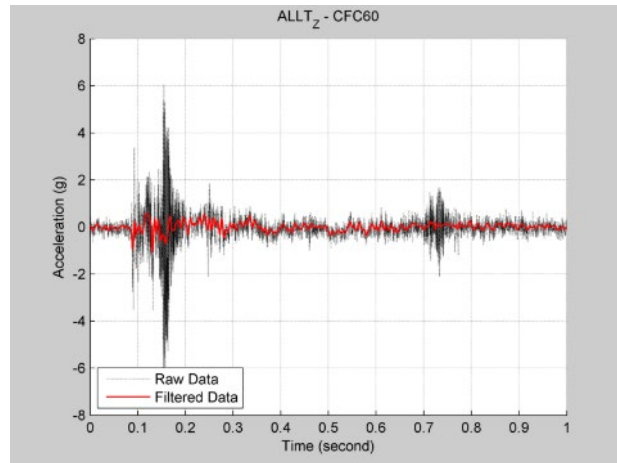


Figure C6. ALLT_Z Accelerometer Data

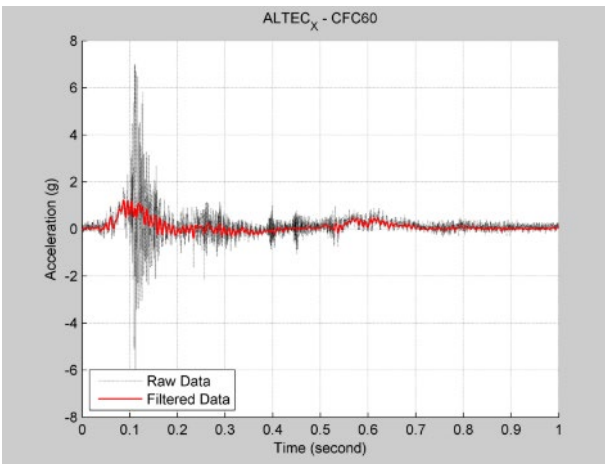


Figure C7. ALTEC_X Accelerometer Data

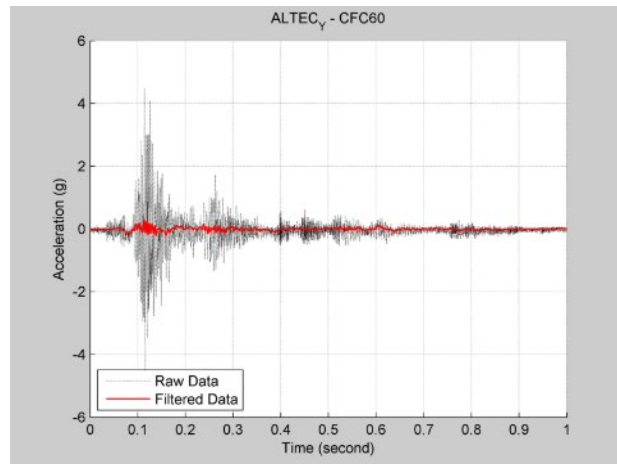


Figure C8. ALTEC_Y Accelerometer Data

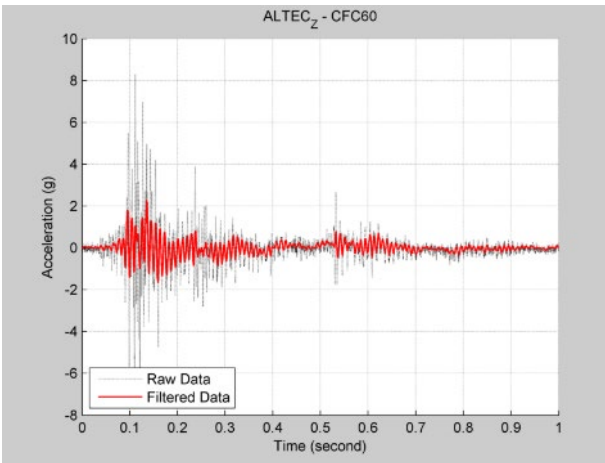


Figure C9. ALTEC_Z Accelerometer Data

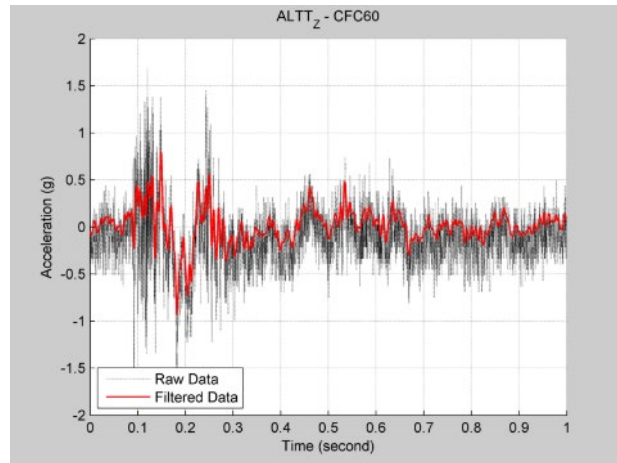


Figure C10. ALTT_Z Accelerometer Data

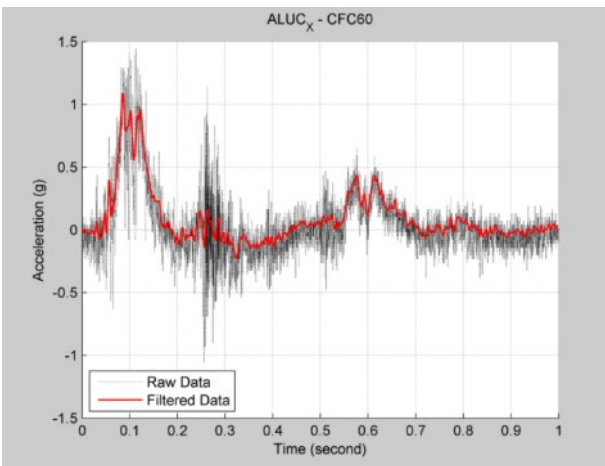


Figure C11. ALUC_X Accelerometer Data

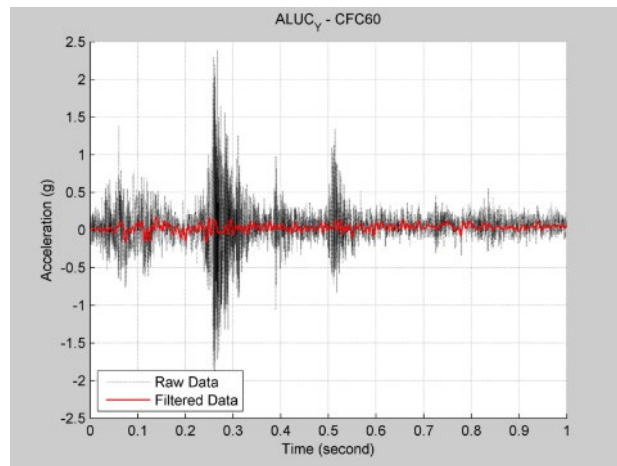


Figure C12. ALUC_Y Accelerometer Data

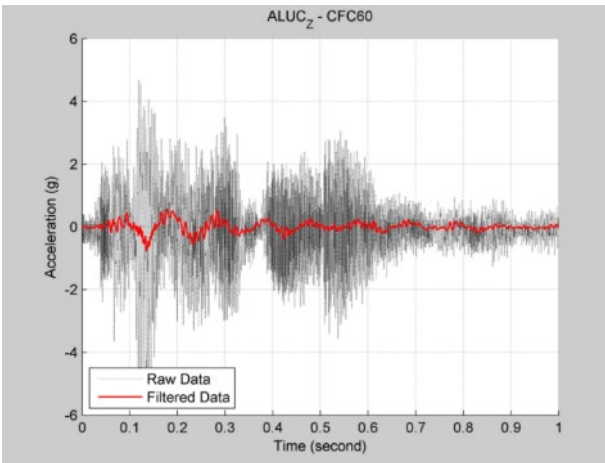


Figure C13. ALUC_Z Accelerometer Data

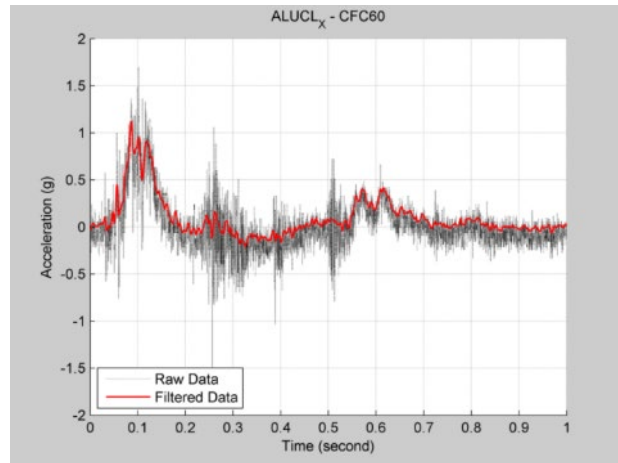


Figure C14. ALUCL_X Accelerometer Data

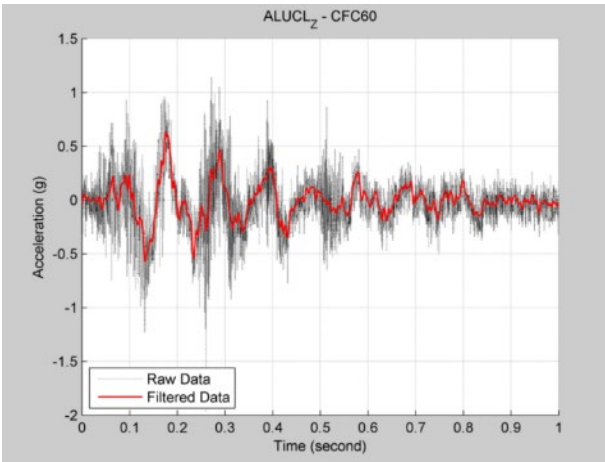


Figure C15. ALUCL_Z Accelerometer Data

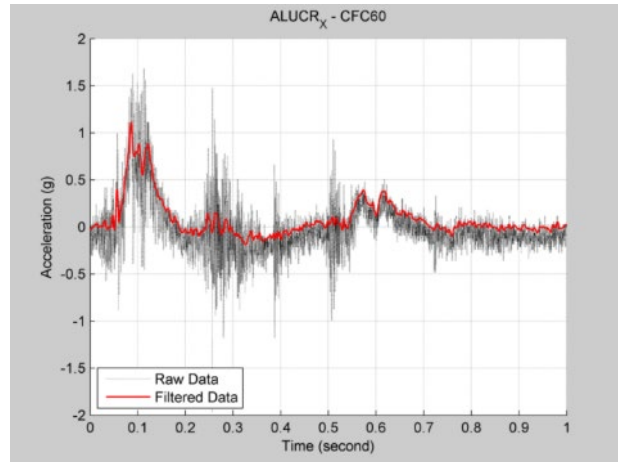


Figure C16. ALUCR_X Accelerometer Data

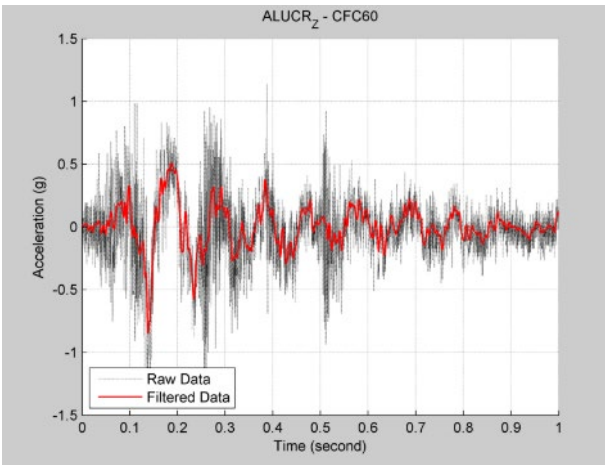


Figure C17. ALUCR_Z Accelerometer Data

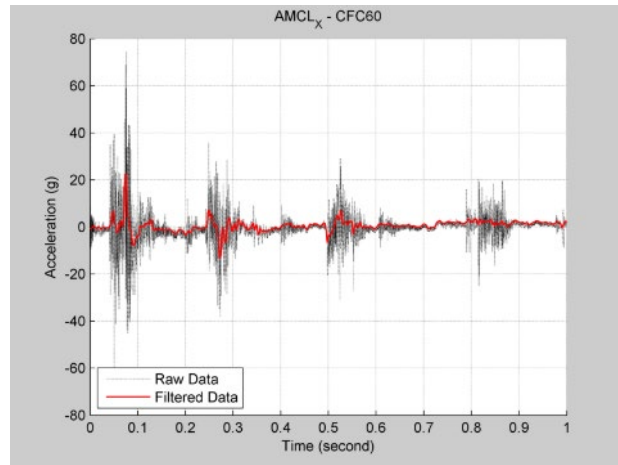


Figure C18. AMCL_X Accelerometer Data

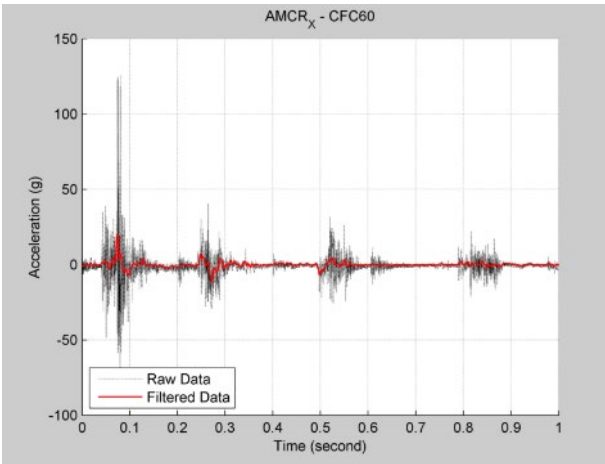


Figure C19. AMCR_X Accelerometer Data

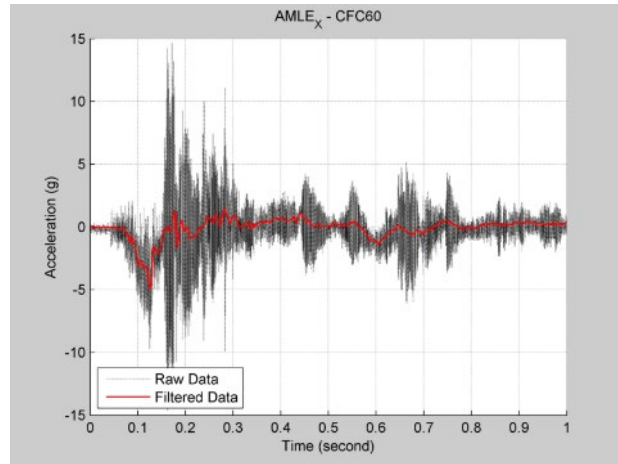


Figure C20. AMLE_X Accelerometer Data

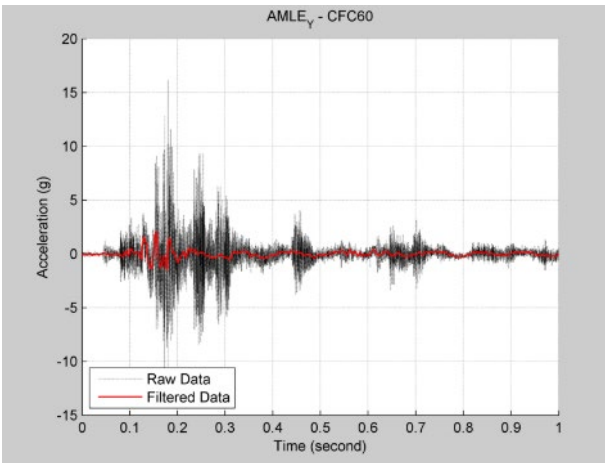


Figure C21. AMLE_Y Accelerometer Data

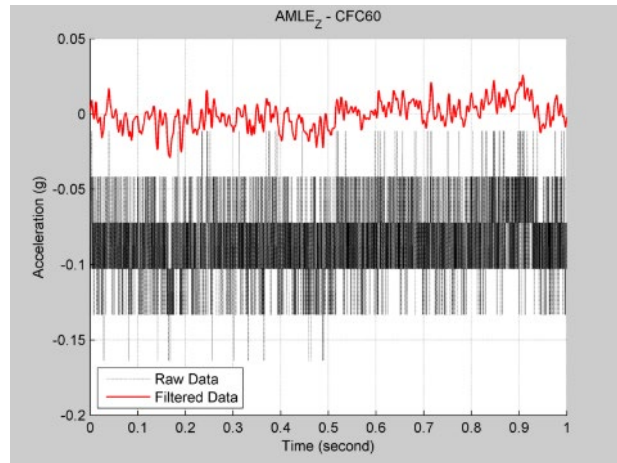


Figure C22. AMLE_Z Accelerometer Data

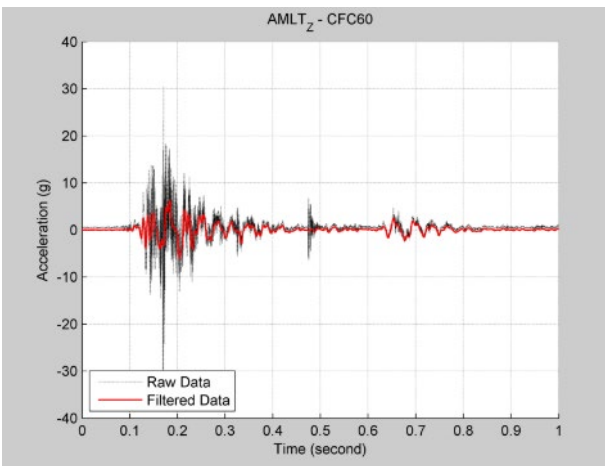


Figure C23. AMLT_Z Accelerometer Data

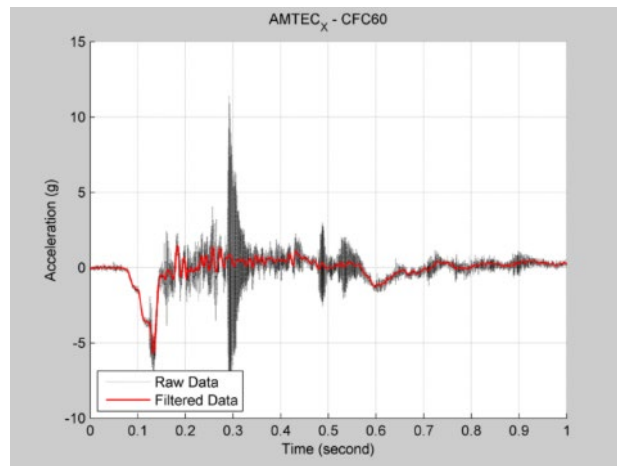


Figure C24. AMTEC_X Accelerometer Data

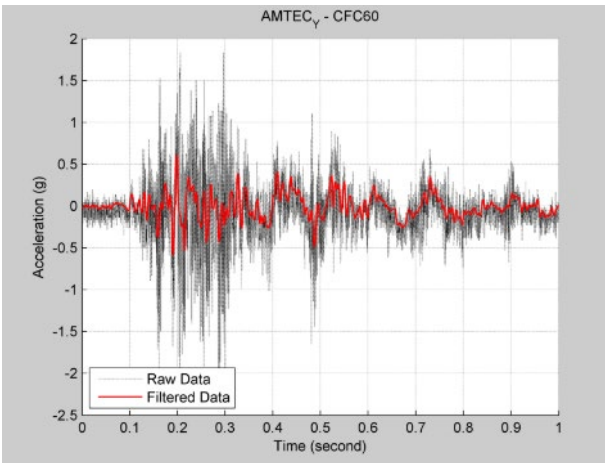


Figure C25. AMTEC_Y Accelerometer Data

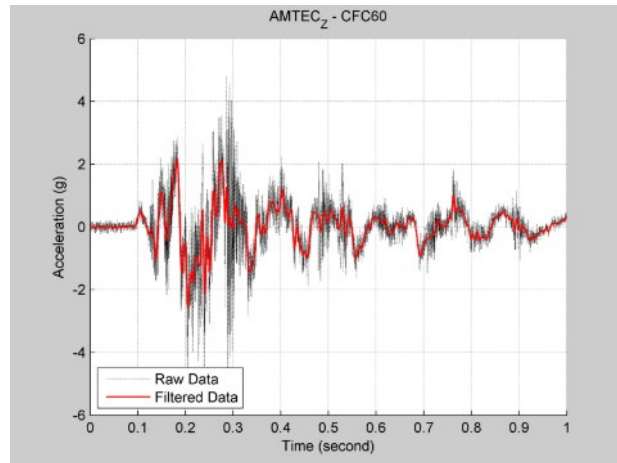


Figure C26. AMTEC_Z Accelerometer Data

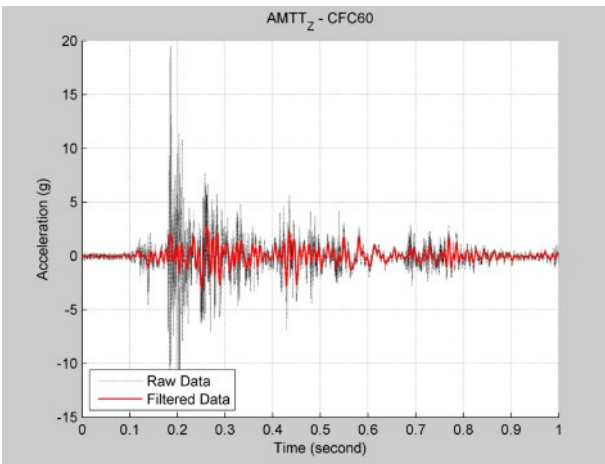


Figure C27. AMTT_Z Accelerometer Data

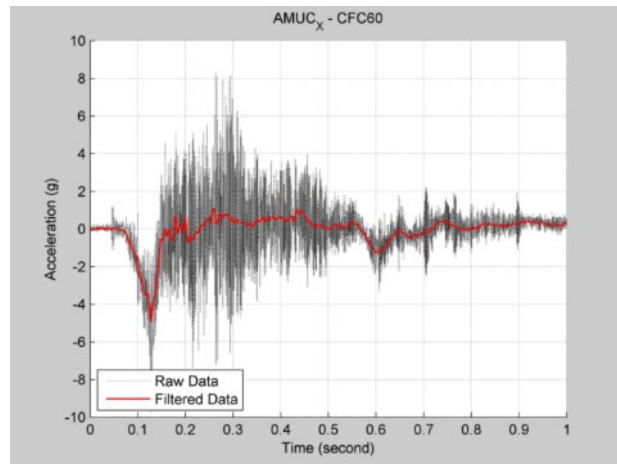


Figure C28. AMUC_X Accelerometer Data

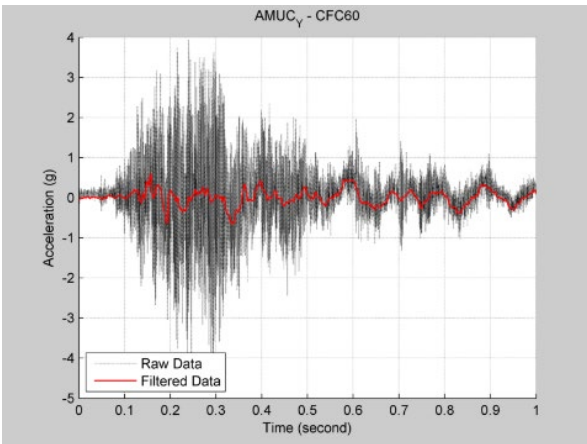


Figure C29. AMUC_Y Accelerometer Data

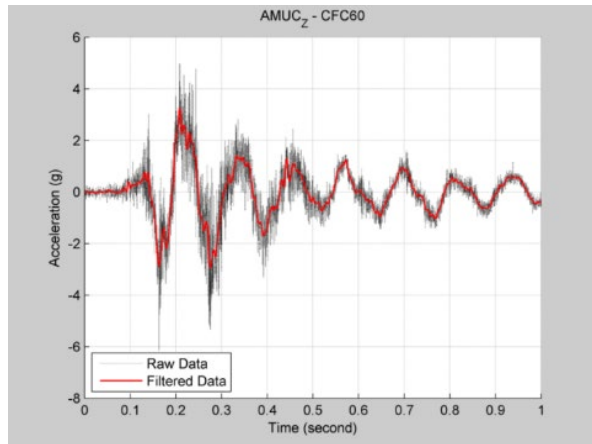


Figure C30. AMUC_Z Accelerometer Data

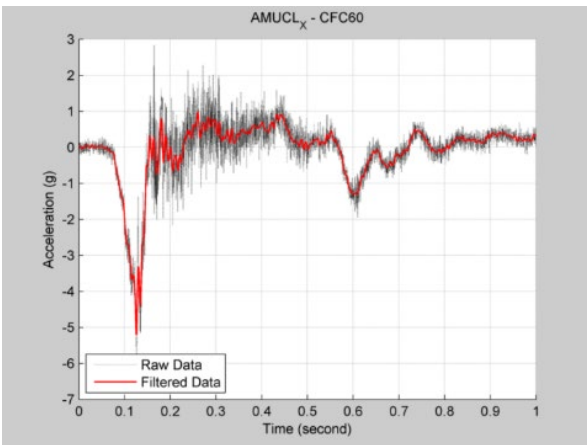


Figure C31. AMUCL_X Accelerometer Data

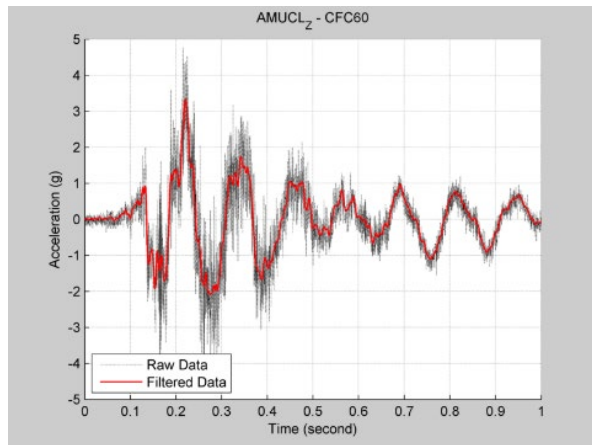


Figure C32. AMUCL_Z Accelerometer Data

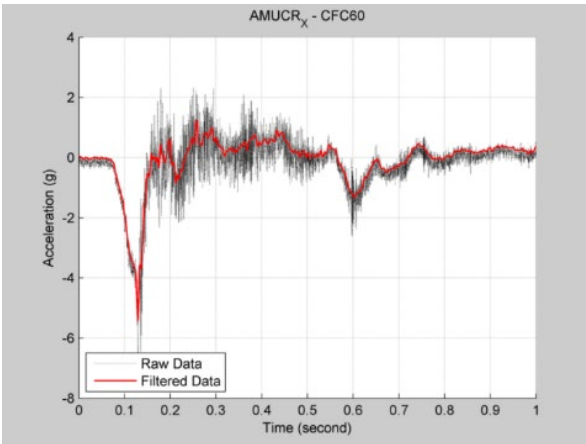


Figure C33. AMUCR_X Accelerometer Data

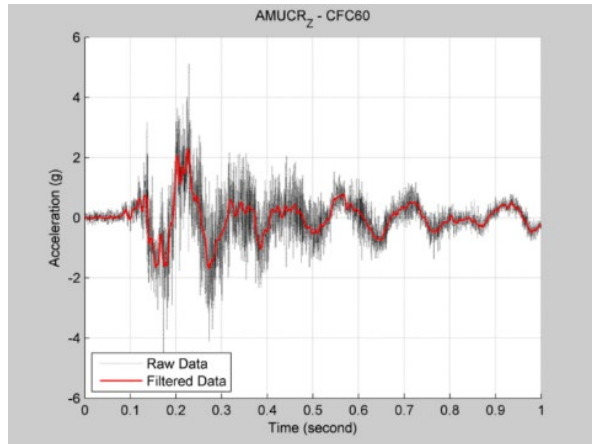


Figure C34. AMUCR_Z Accelerometer Data

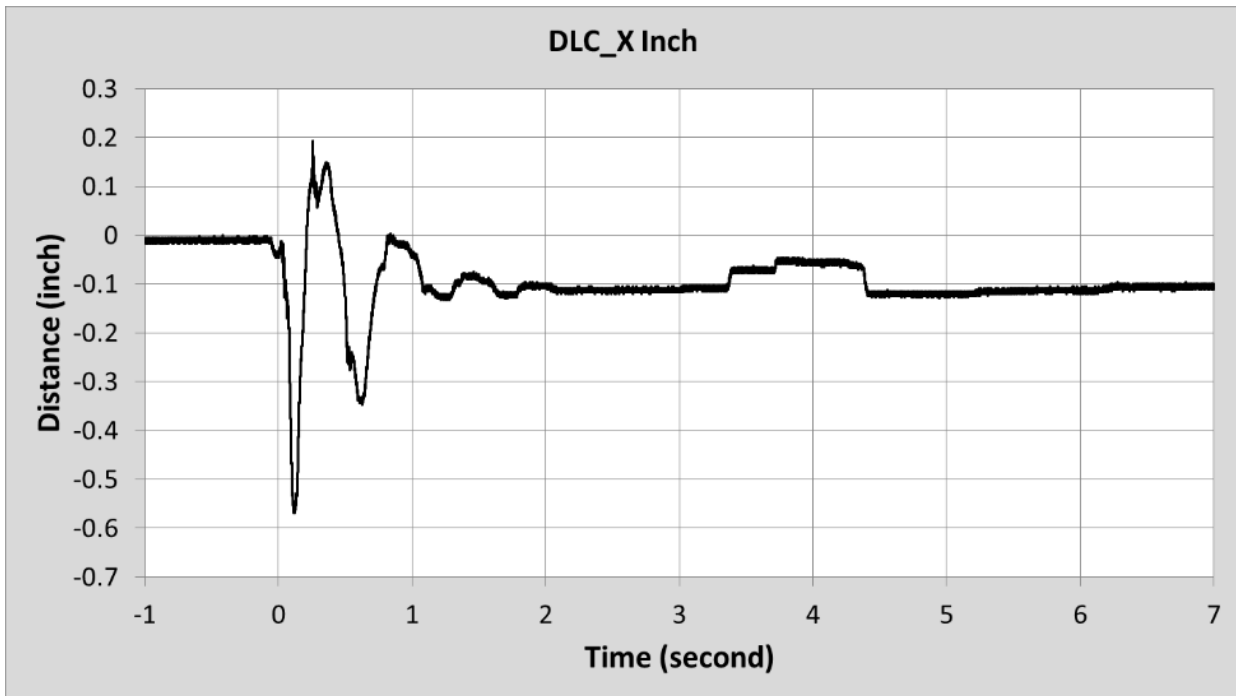


Figure C35. DLC_X String Potentiometer Data

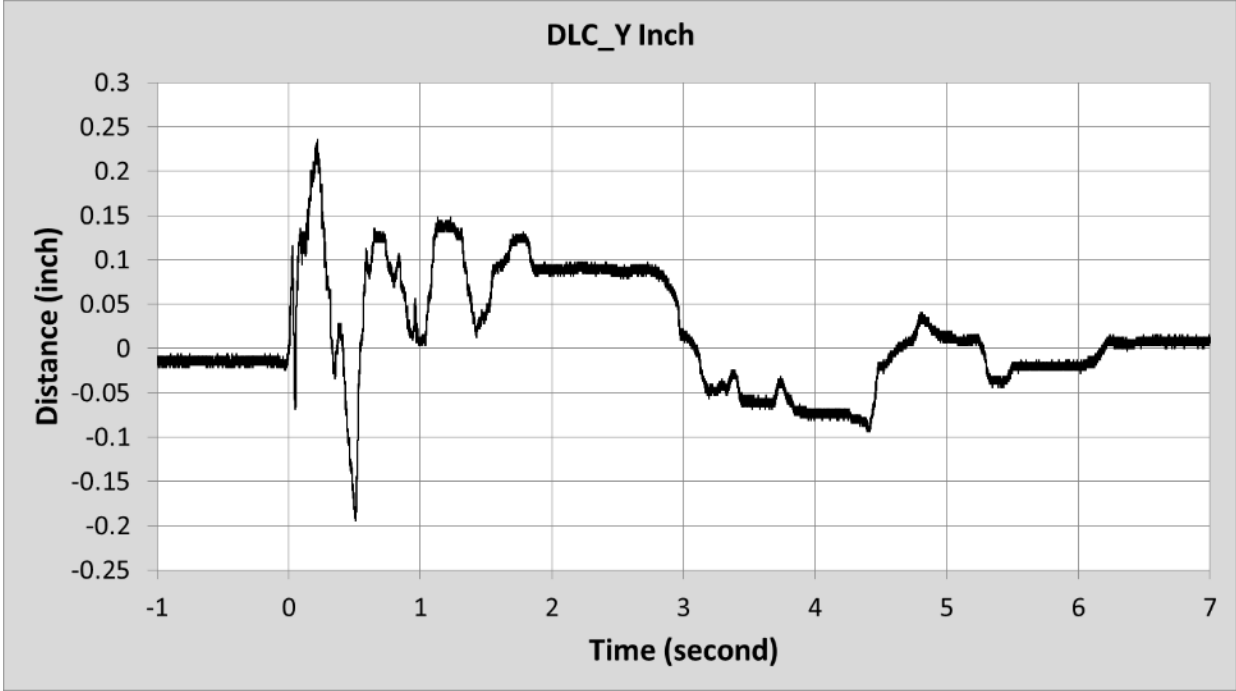


Figure C36. DLC_Y String Potentiometer Data

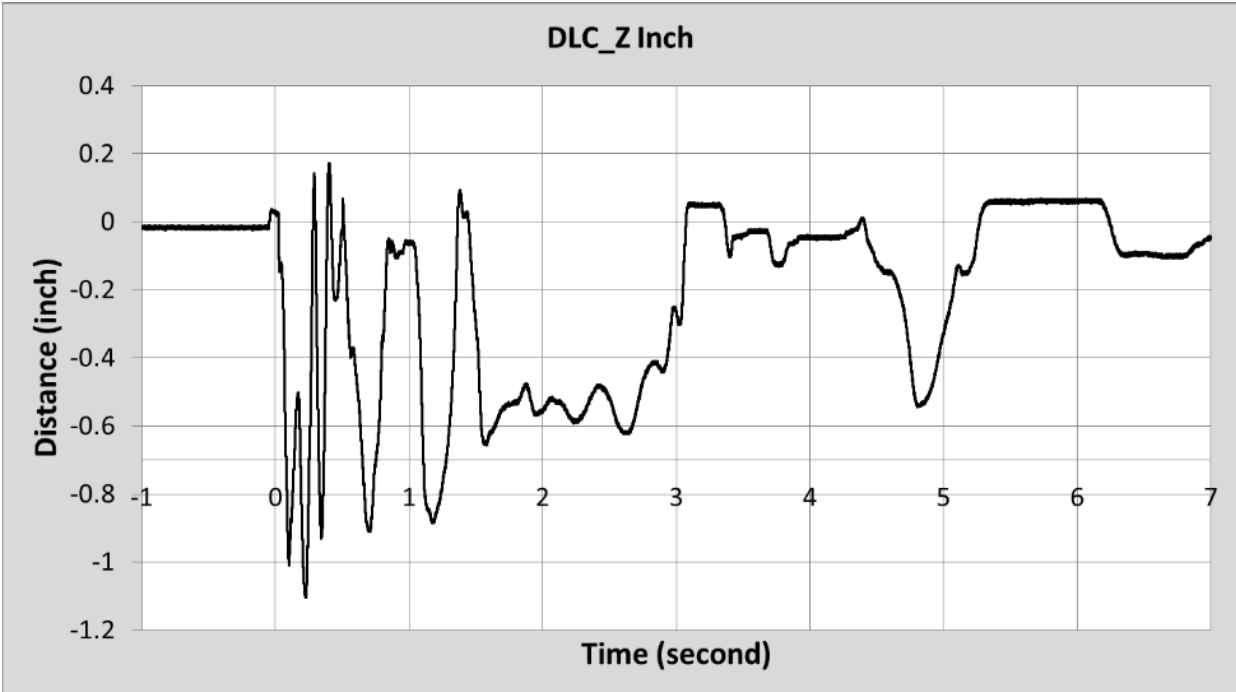


Figure C37. DLC_Z String Potentiometer Data

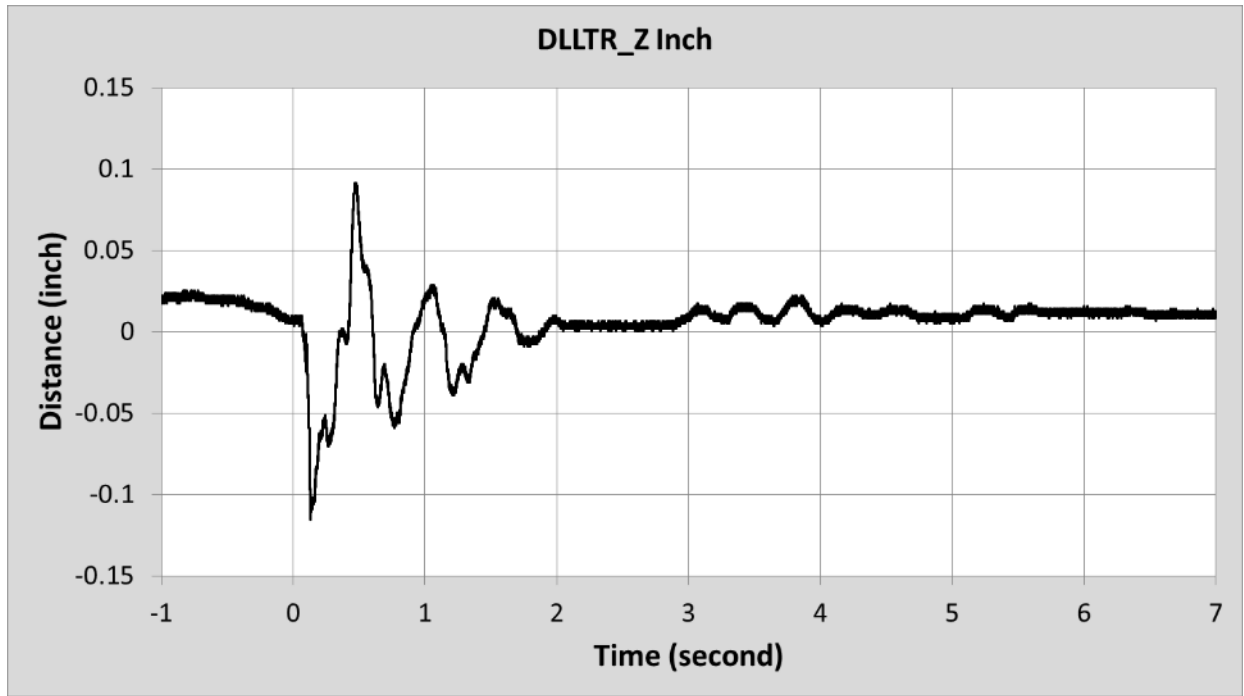


Figure C38. DLLTR_Z String Potentiometer Data

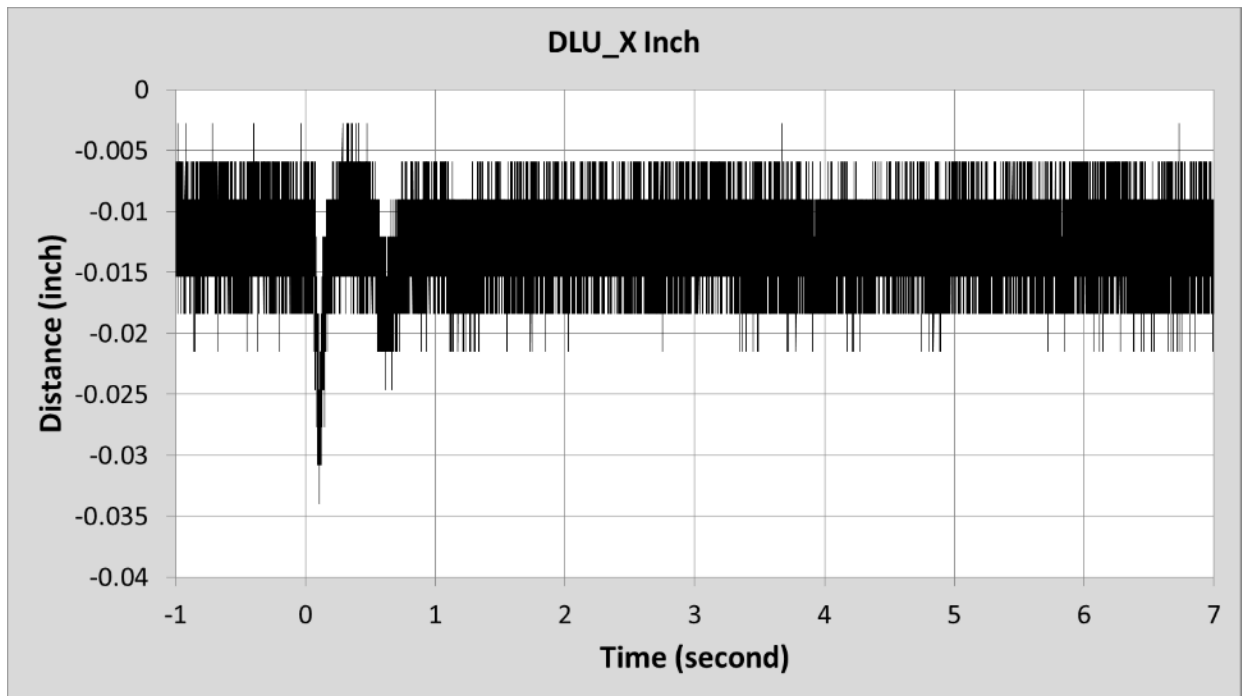


Figure C39. DLU_X String Potentiometer Data

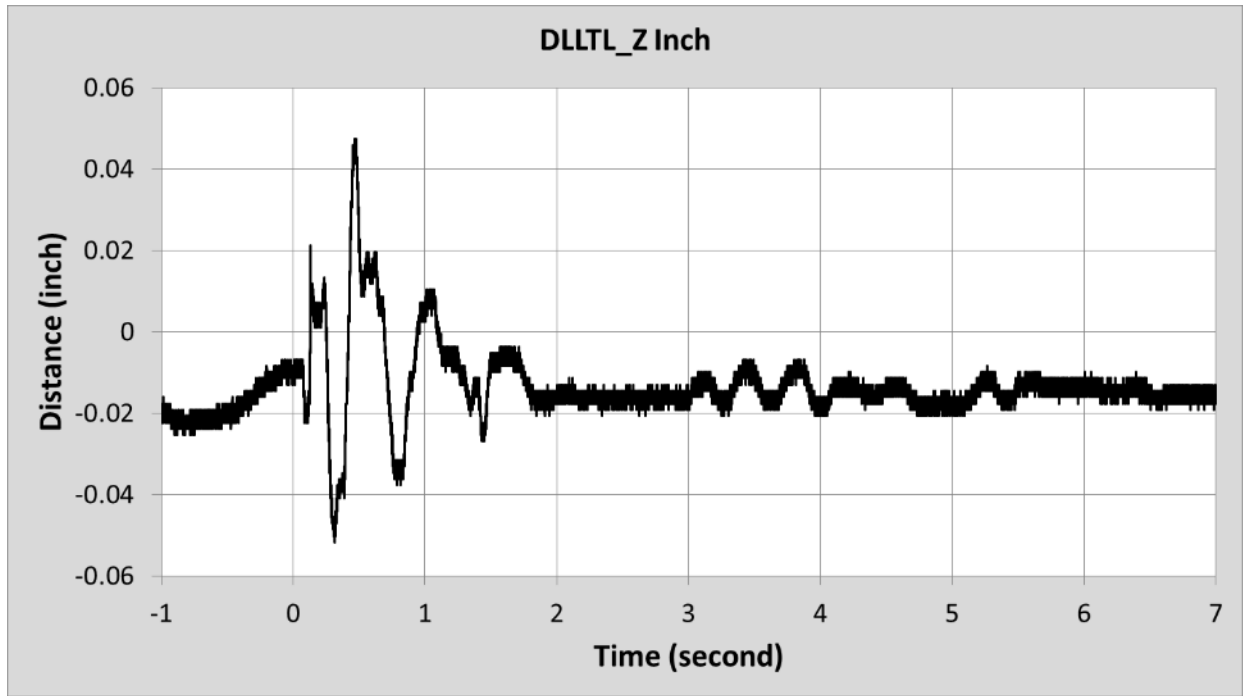


Figure C40. DLLTL_Z String Potentiometer Data

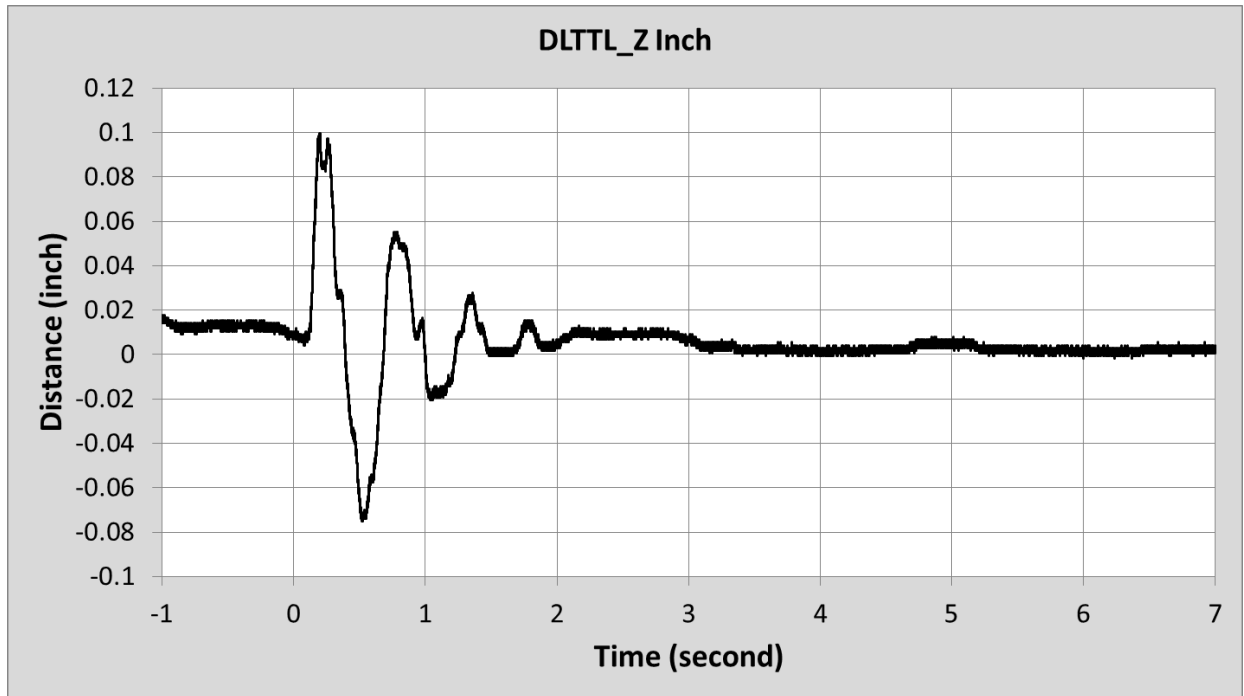


Figure C41. DLTTL_Z String Potentiometer Data

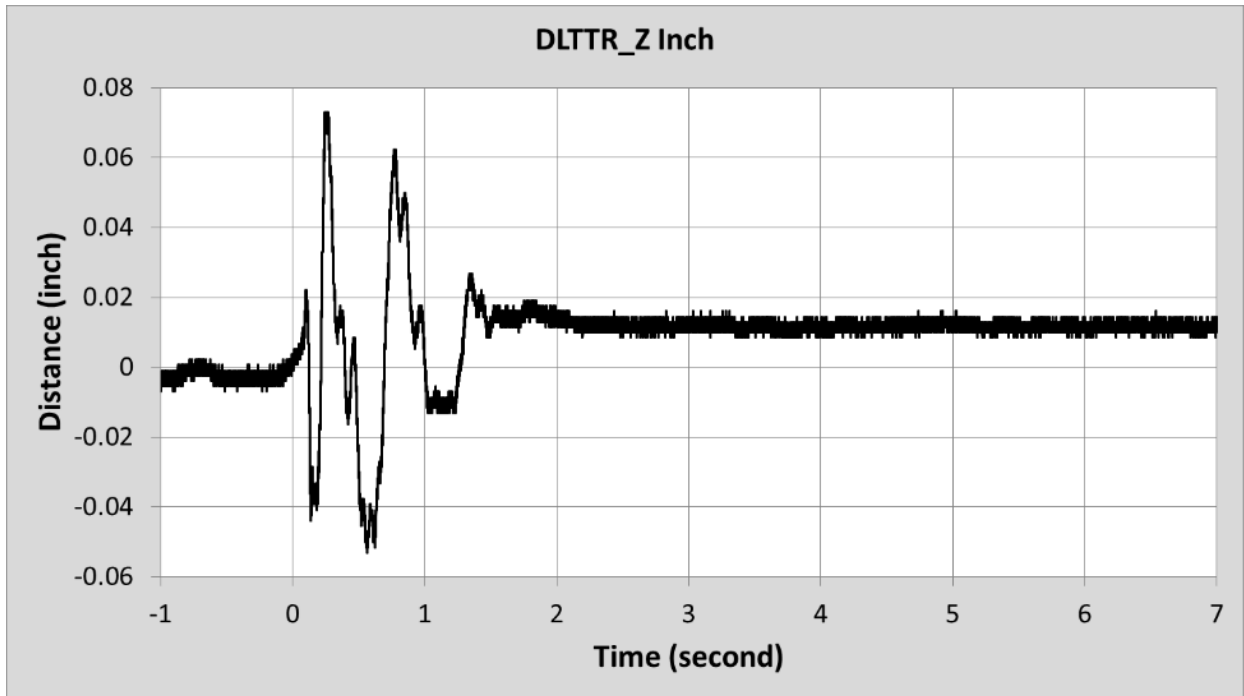


Figure C42. DLTTR_Z String Potentiometer Data

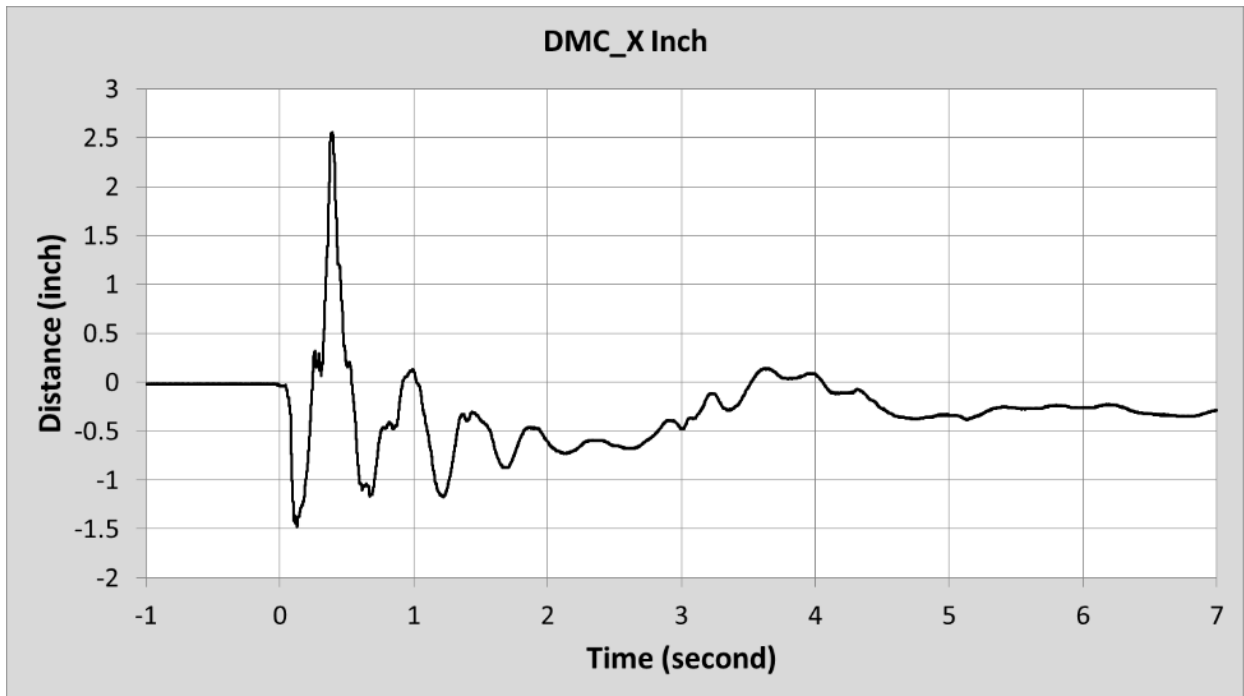


Figure C43. DMC_X String Potentiometer Data

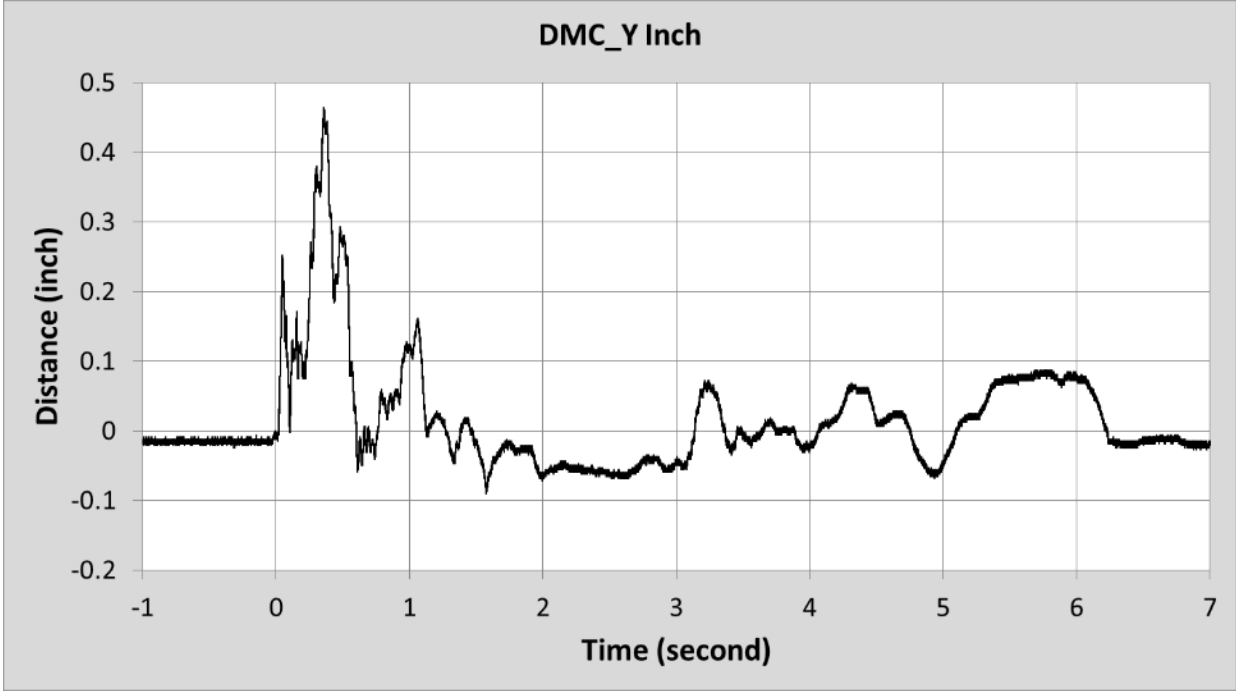


Figure C44. DMC_Y String Potentiometer Data

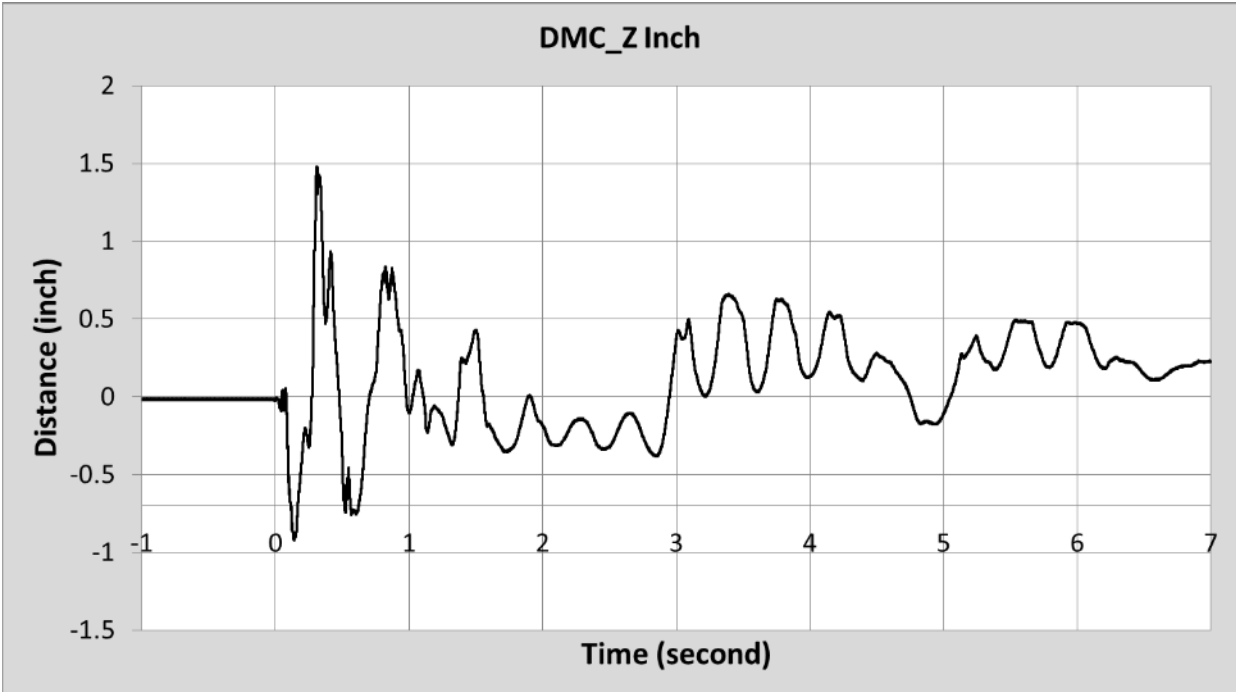


Figure C45. DMC_Z String Potentiometer Data

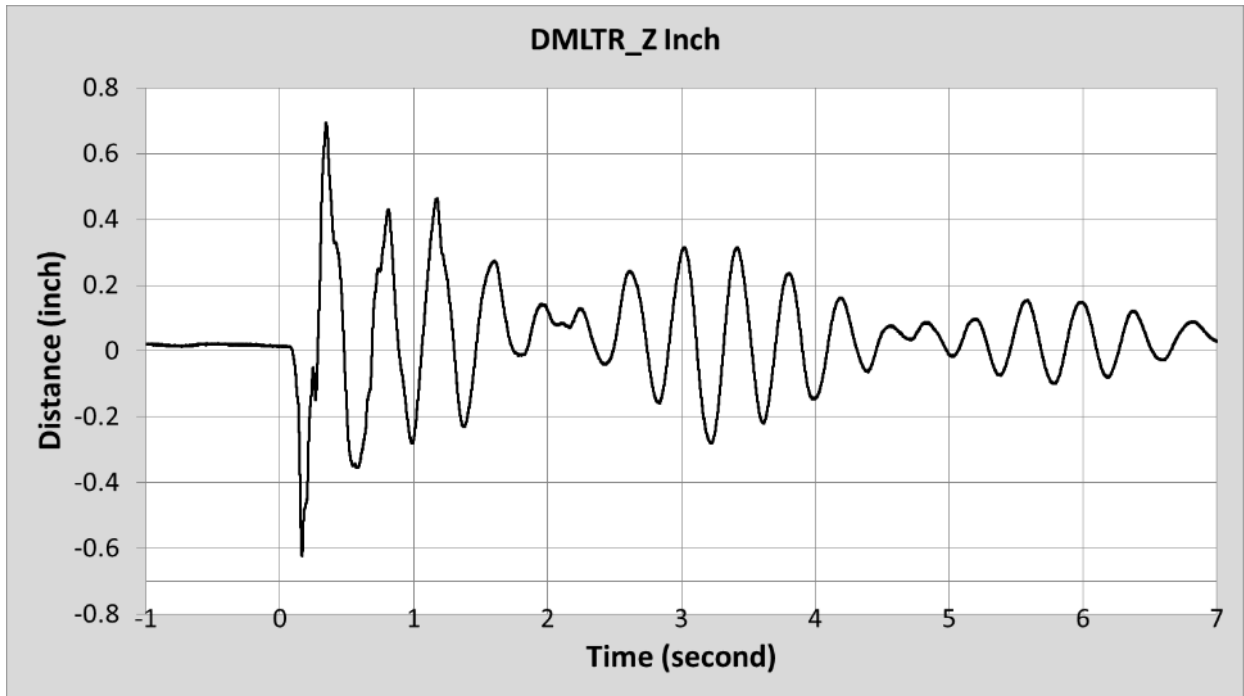


Figure C46. DMLTR_Z String Potentiometer Data

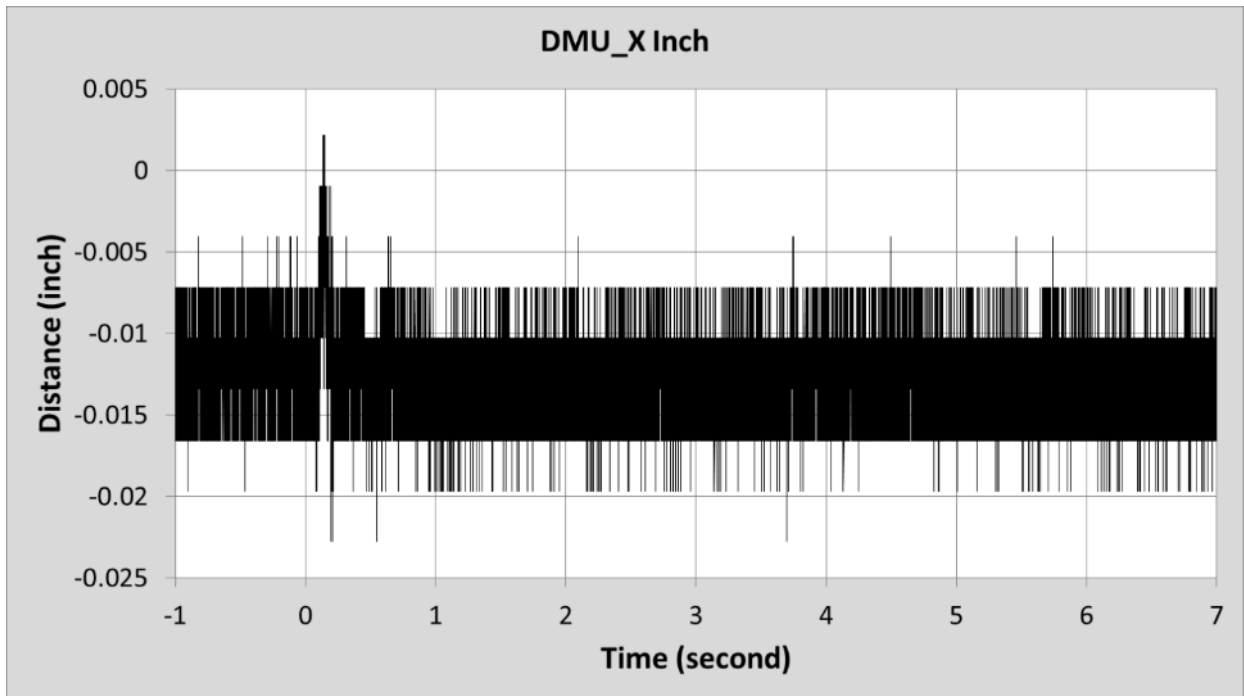


Figure C47. DMU_X String Potentiometer Data

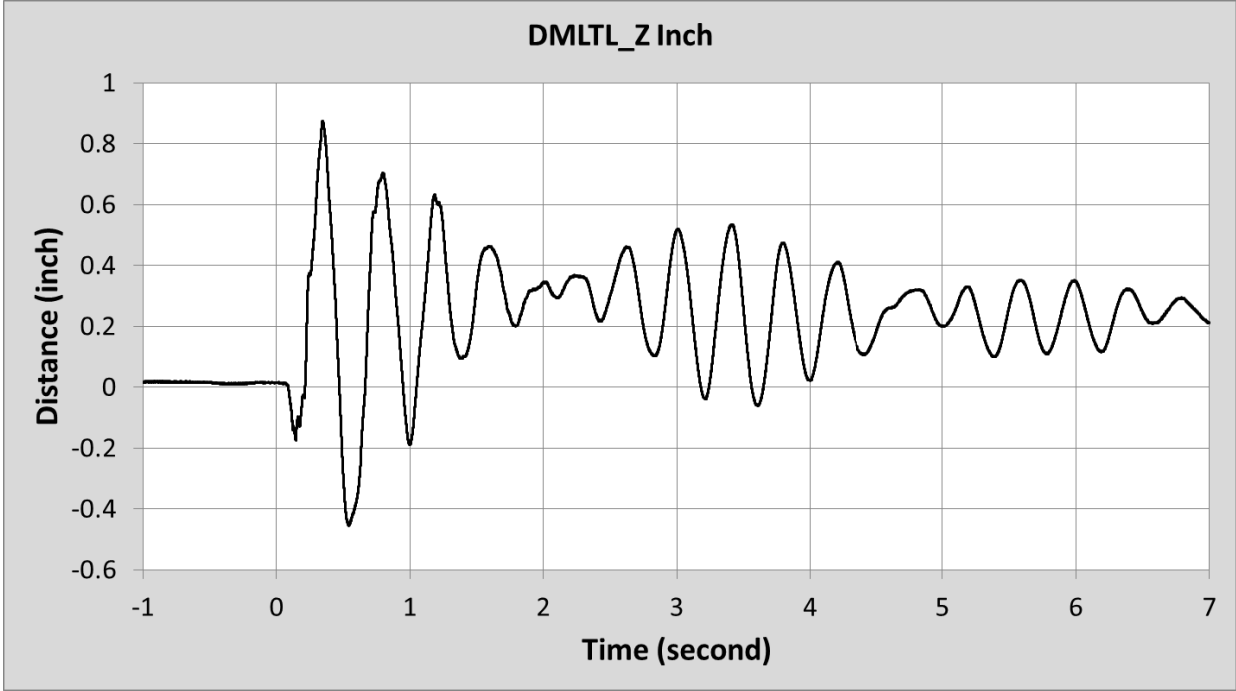


Figure C48. DMLTL_Z String Potentiometer Data

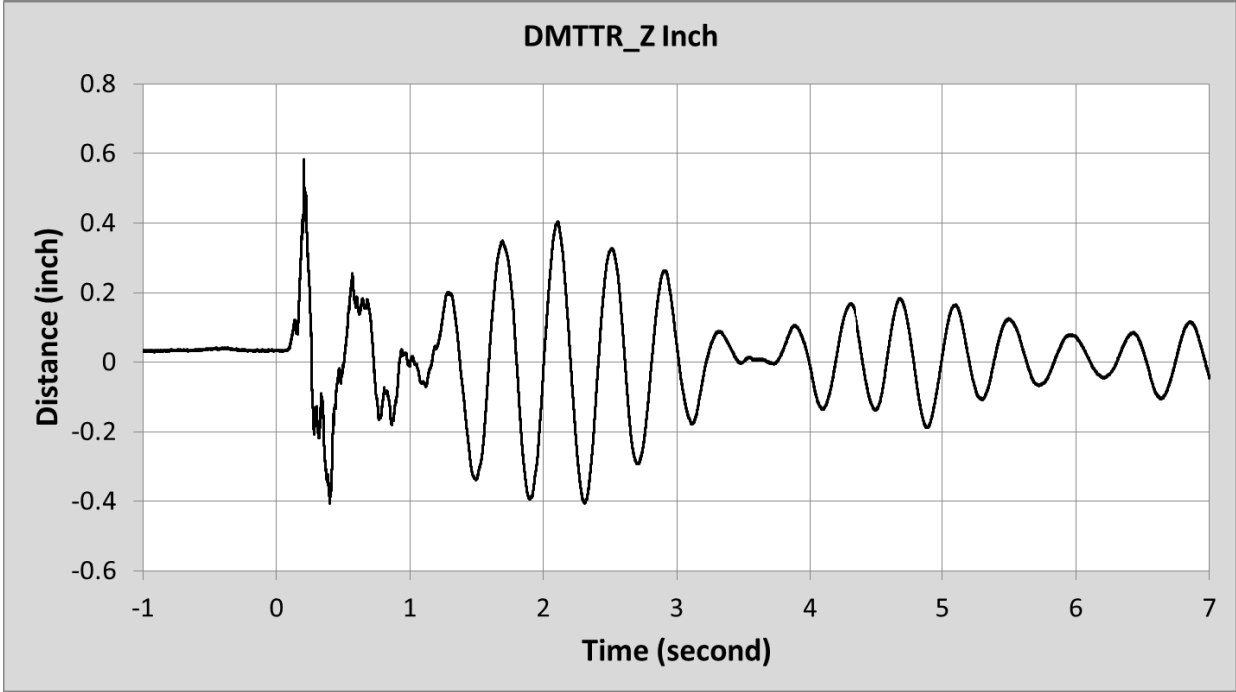


Figure C49. DMTTR_Z String Potentiometer Data

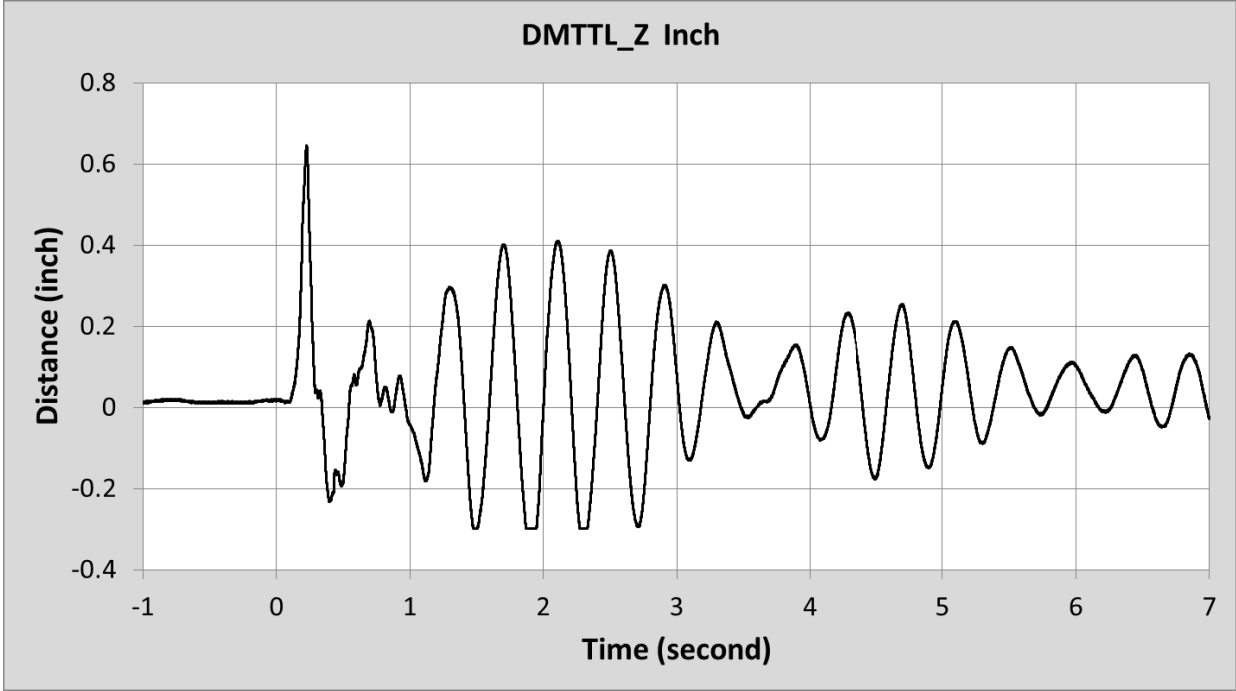


Figure C50. DMTTL_Z String Potentiometer Data

Appendix D. 6 mph Test Data

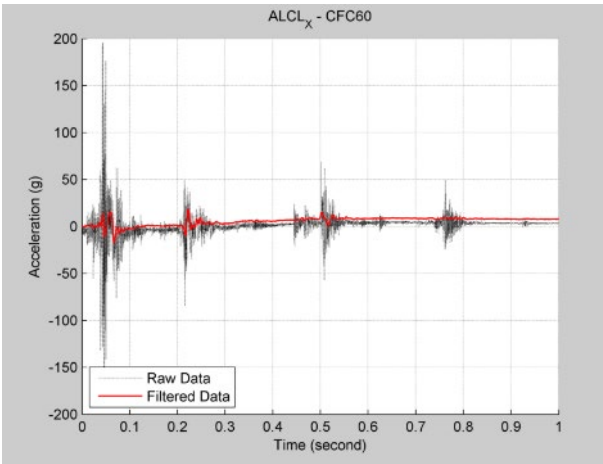


Figure D1. ALCL_X Accelerometer Data

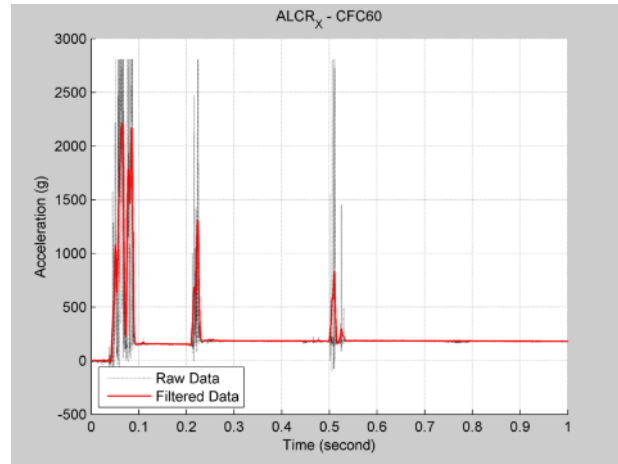


Figure D2. ALCR_X Accelerometer Data

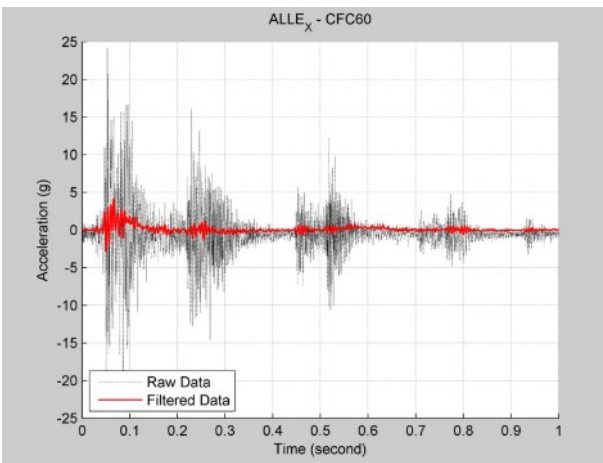


Figure D3. ALLE_X Accelerometer Data

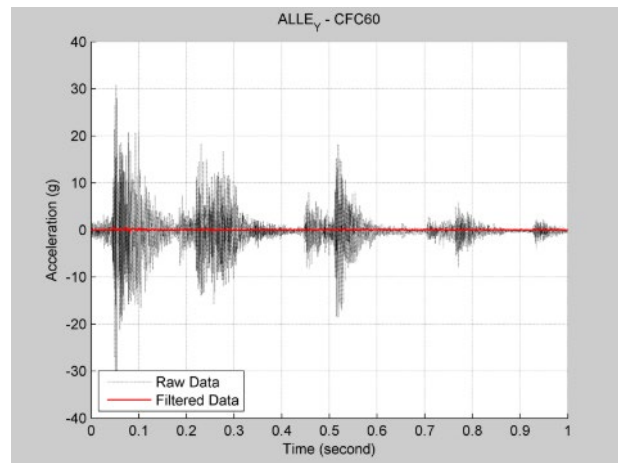


Figure D4. ALLE_Y Accelerometer Data

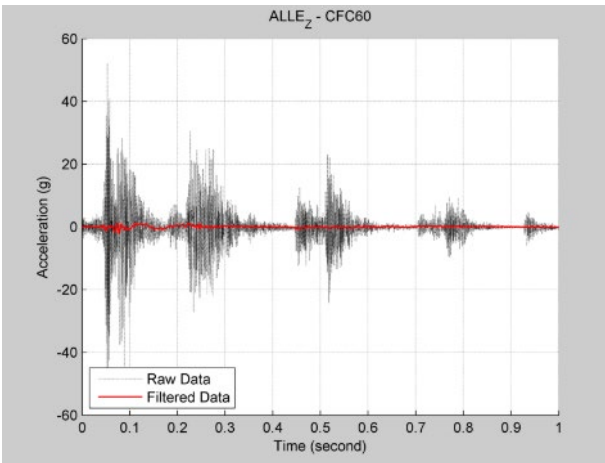


Figure D5. ALLE_Z Accelerometer Data

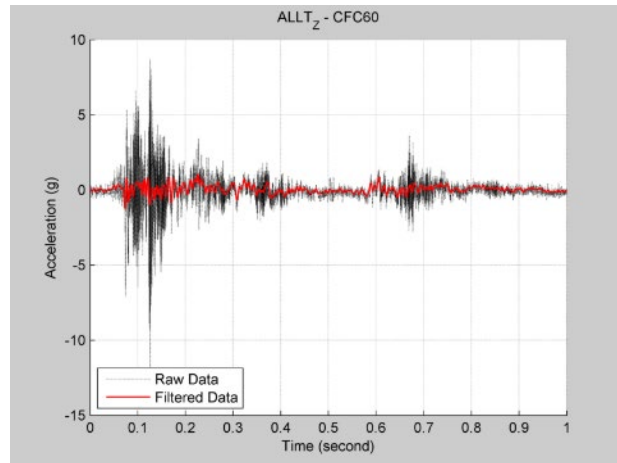


Figure D6. ALLT_Z Accelerometer Data

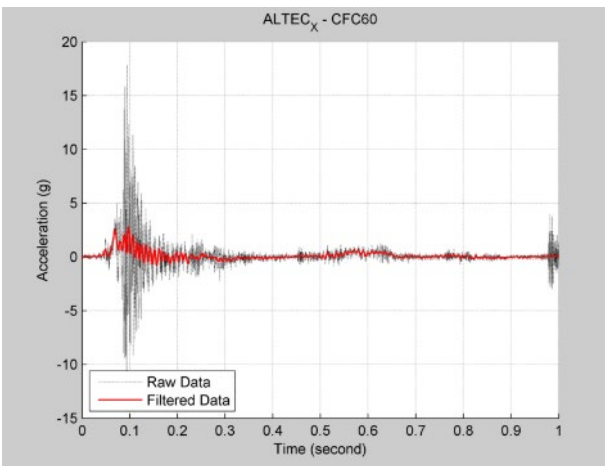


Figure D7. ALTEC_X Accelerometer Data

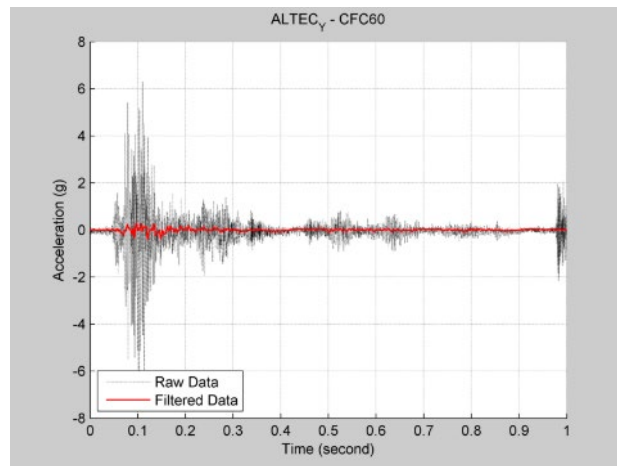


Figure D8. ALTEC_Y Accelerometer Data

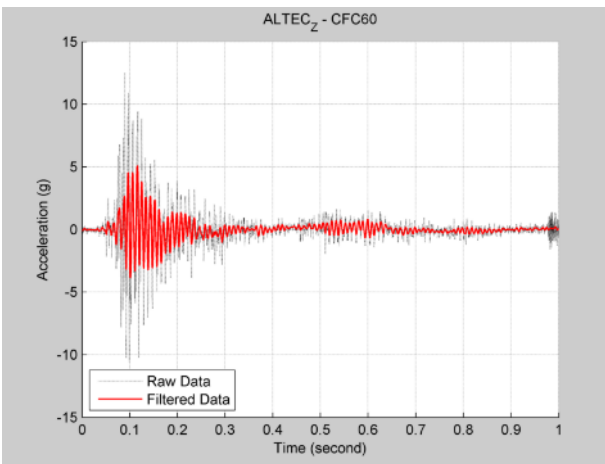


Figure D9. ALTEC_Z Accelerometer Data

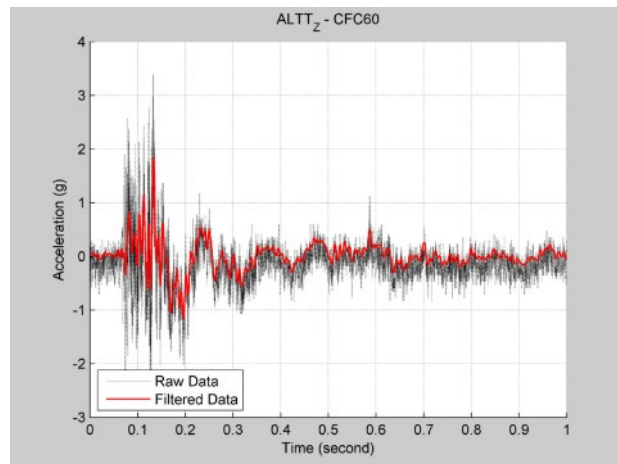


Figure D10. ALTT_Z Accelerometer Data

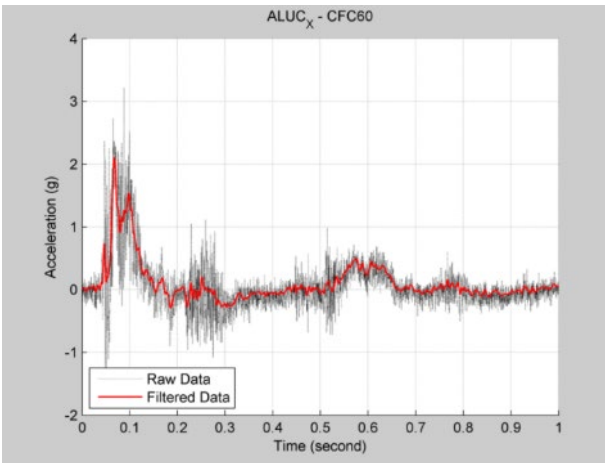


Figure D11. ALUC_X Accelerometer Data

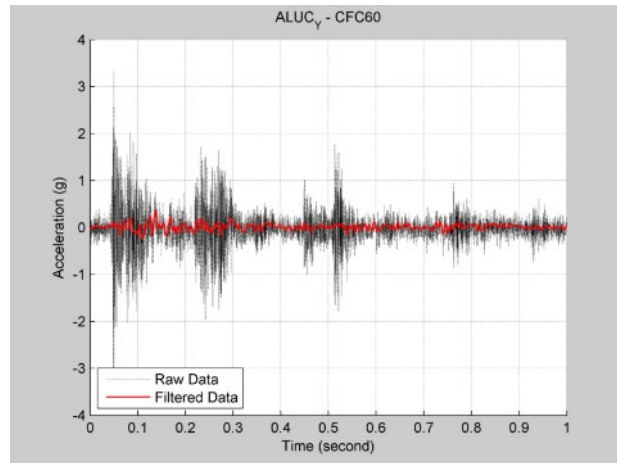


Figure D12. ALUC_Y Accelerometer Data

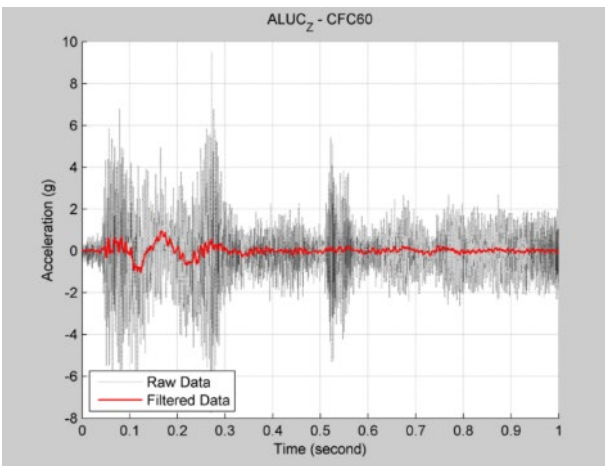


Figure D13. ALUC_Z Accelerometer Data

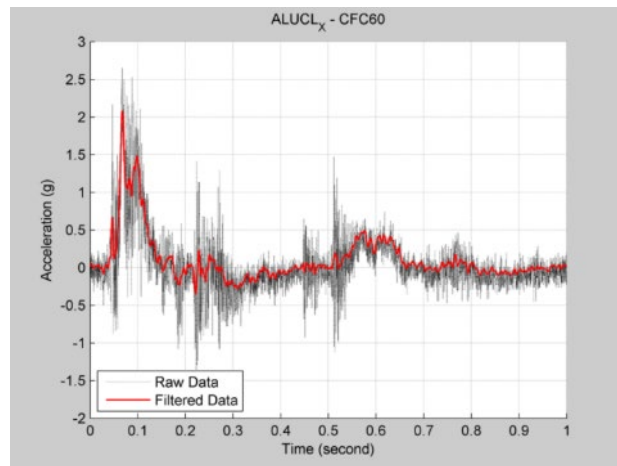


Figure D14. ALUCL_X Accelerometer Data

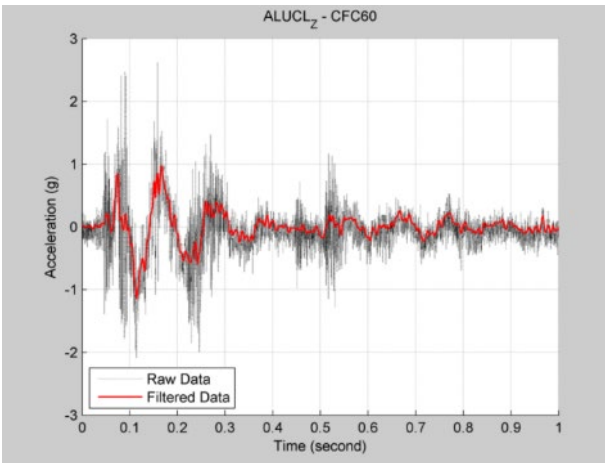


Figure D15. ALUCL_Z Accelerometer Data

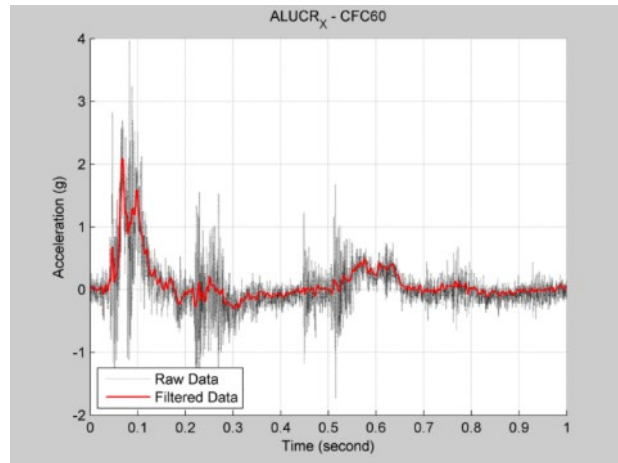


Figure D16. ALUCR_X Accelerometer Data

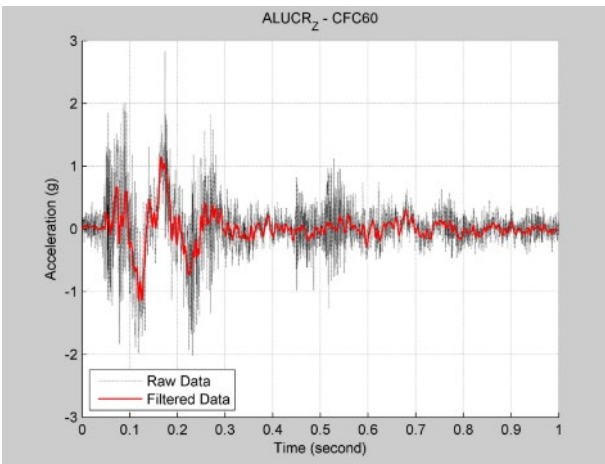


Figure D17. ALUCR_Z Accelerometer Data

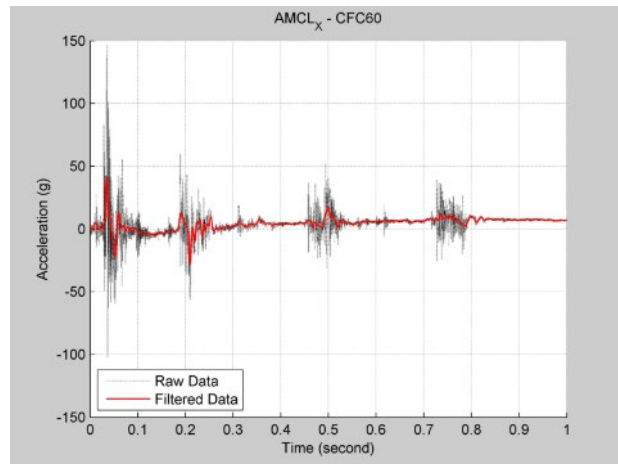


Figure D18. AMCL_X Accelerometer Data

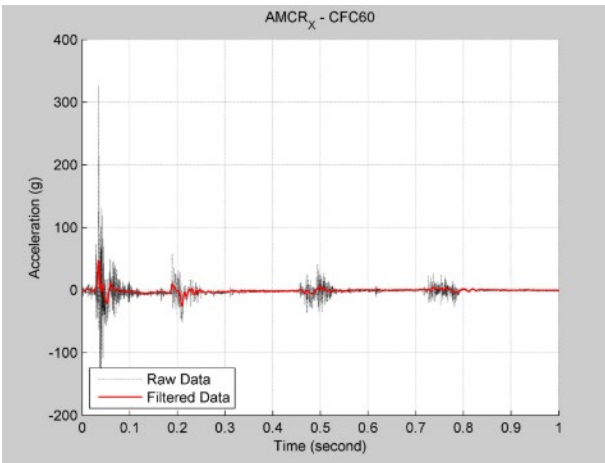


Figure D19. AMCR_X Accelerometer Data

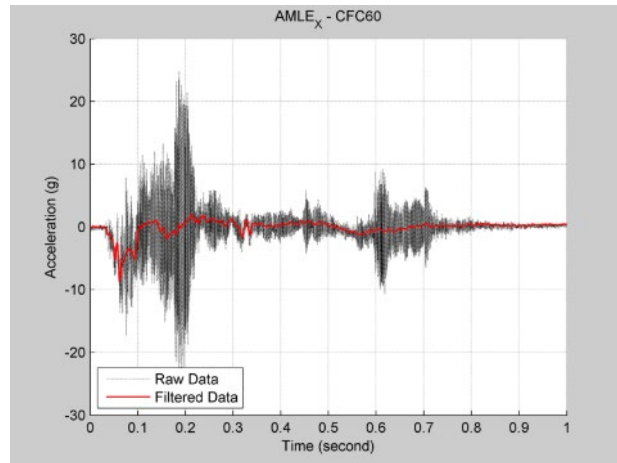


Figure D20. AMLE_X Accelerometer Data

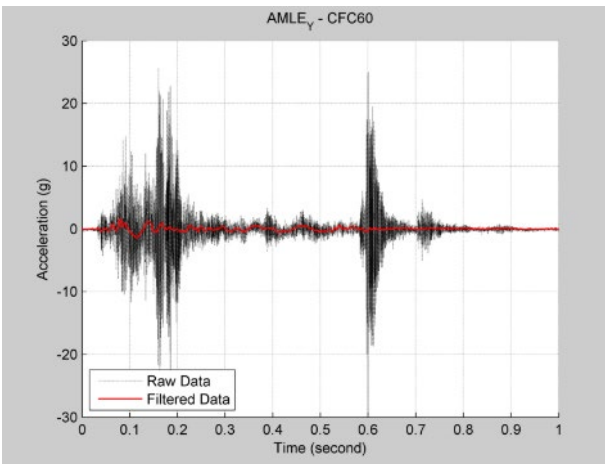


Figure D21. AMLE_Y Accelerometer Data

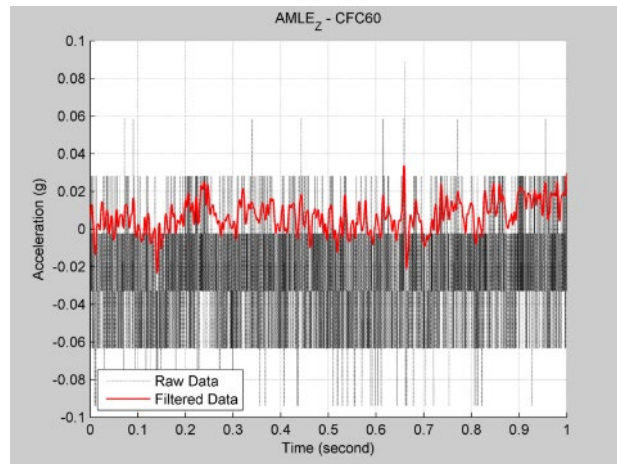


Figure D22. AMLE_Z Accelerometer Data

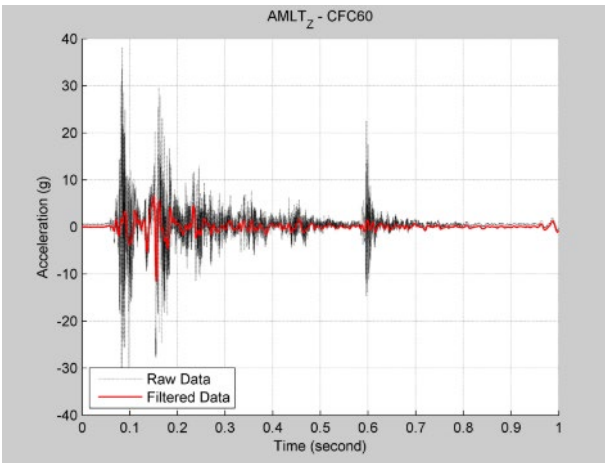


Figure D23. AMLT_Z Accelerometer Data

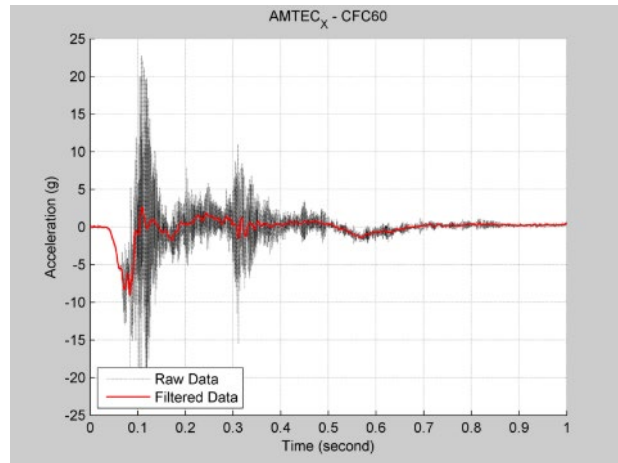


Figure D24. AMTEC_X Accelerometer Data

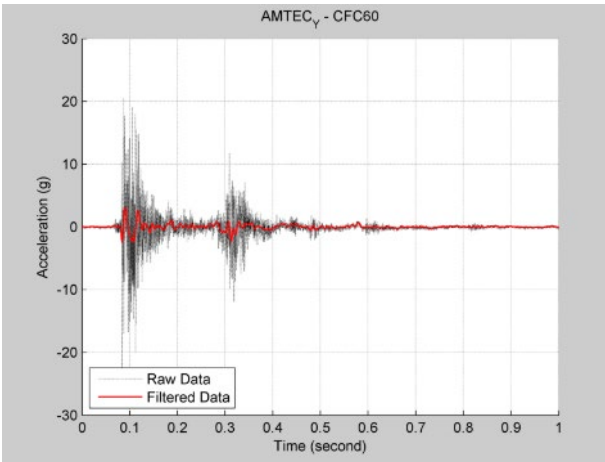


Figure D25. AMTEC_Y Accelerometer Data

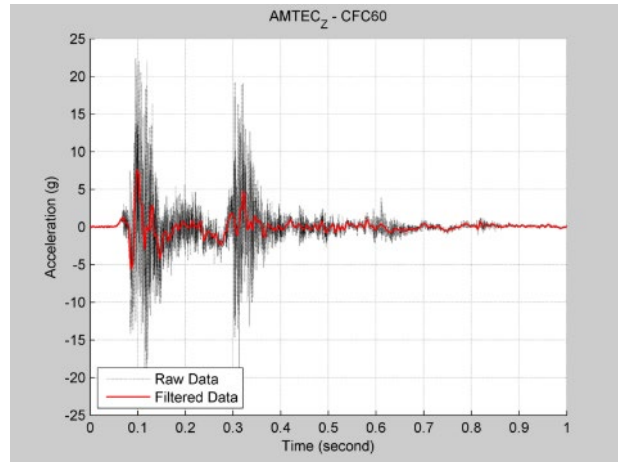


Figure D26. AMTEC_Z Accelerometer Data

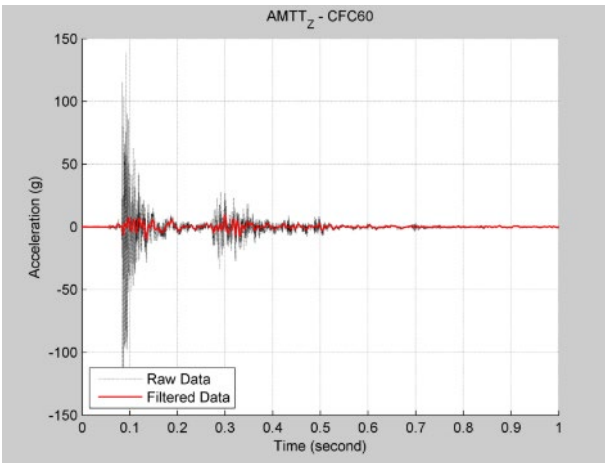


Figure D27. AMTT_Z Accelerometer Data

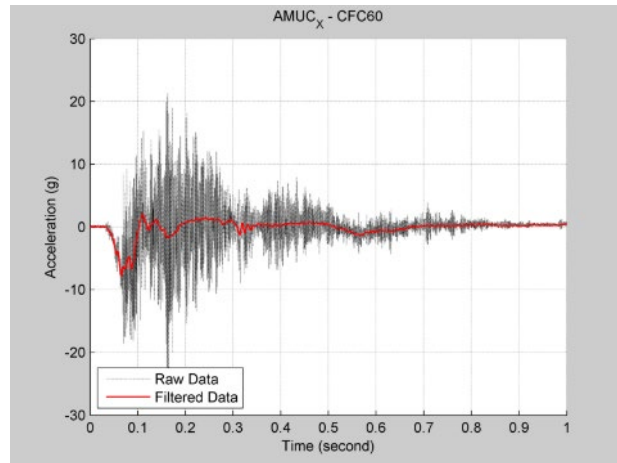


Figure D28. AMUC_X Accelerometer Data

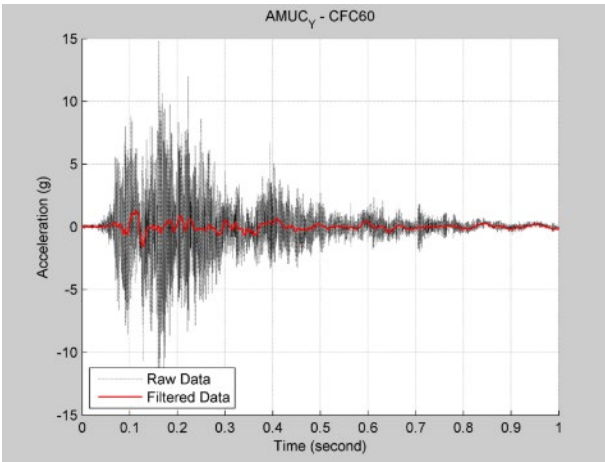


Figure D29. AMUC_Y Accelerometer Data

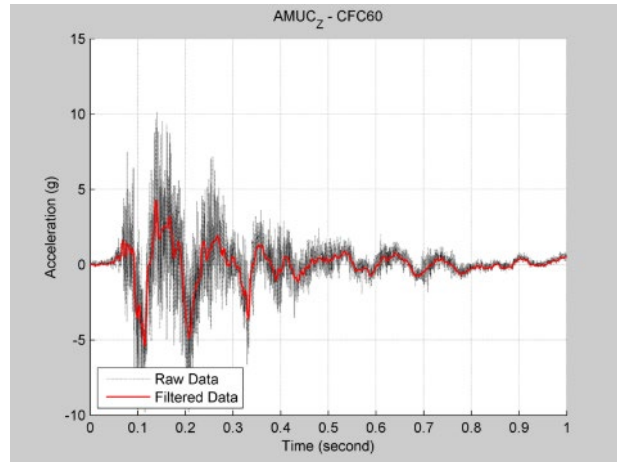


Figure D30. AMUC_Z Accelerometer Data

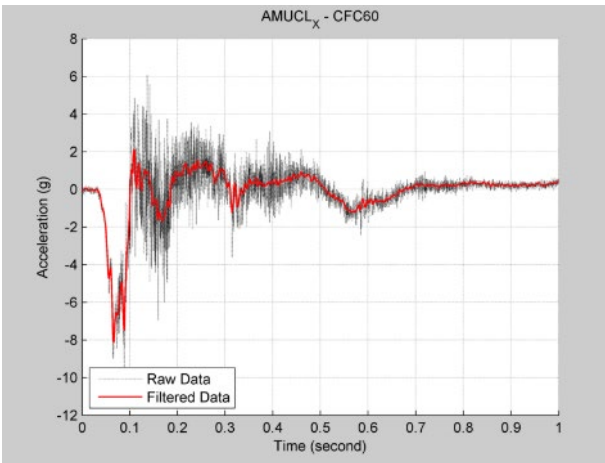


Figure D31. AMUCL_X Accelerometer Data

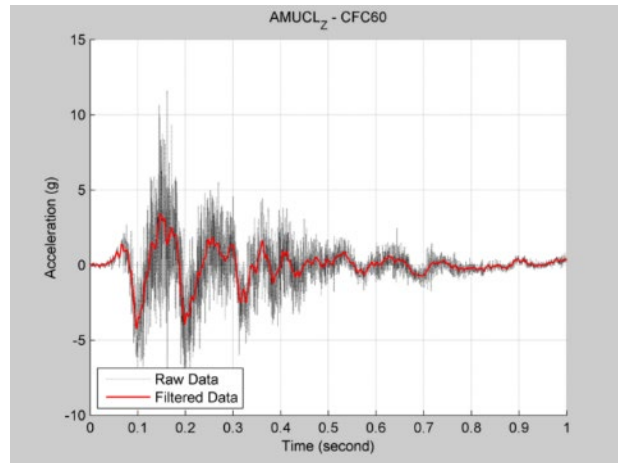


Figure D32. AMUCL_Z Accelerometer Data

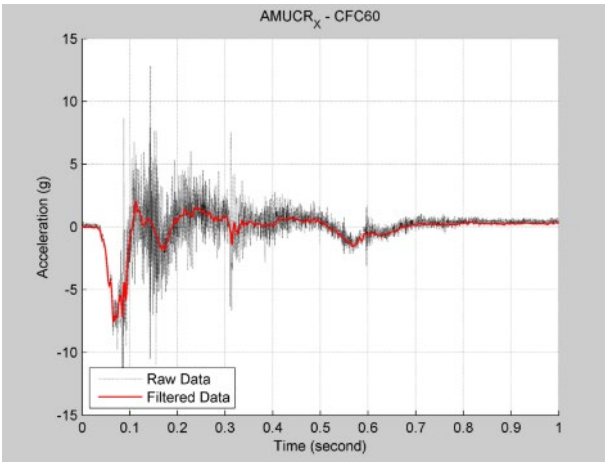


Figure D33. AMUCR_X Accelerometer Data

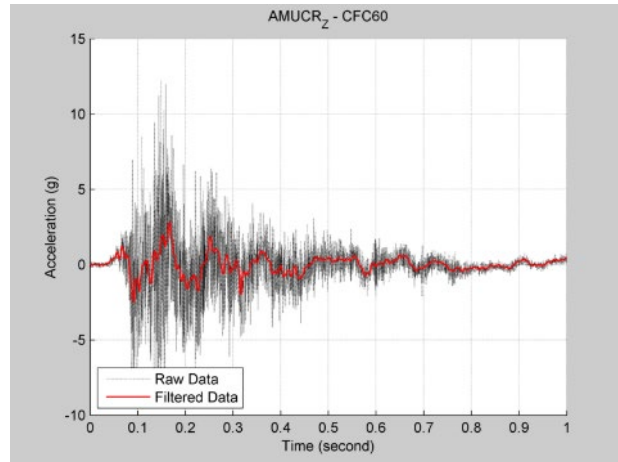


Figure D34. AMUCR_Z Accelerometer Data

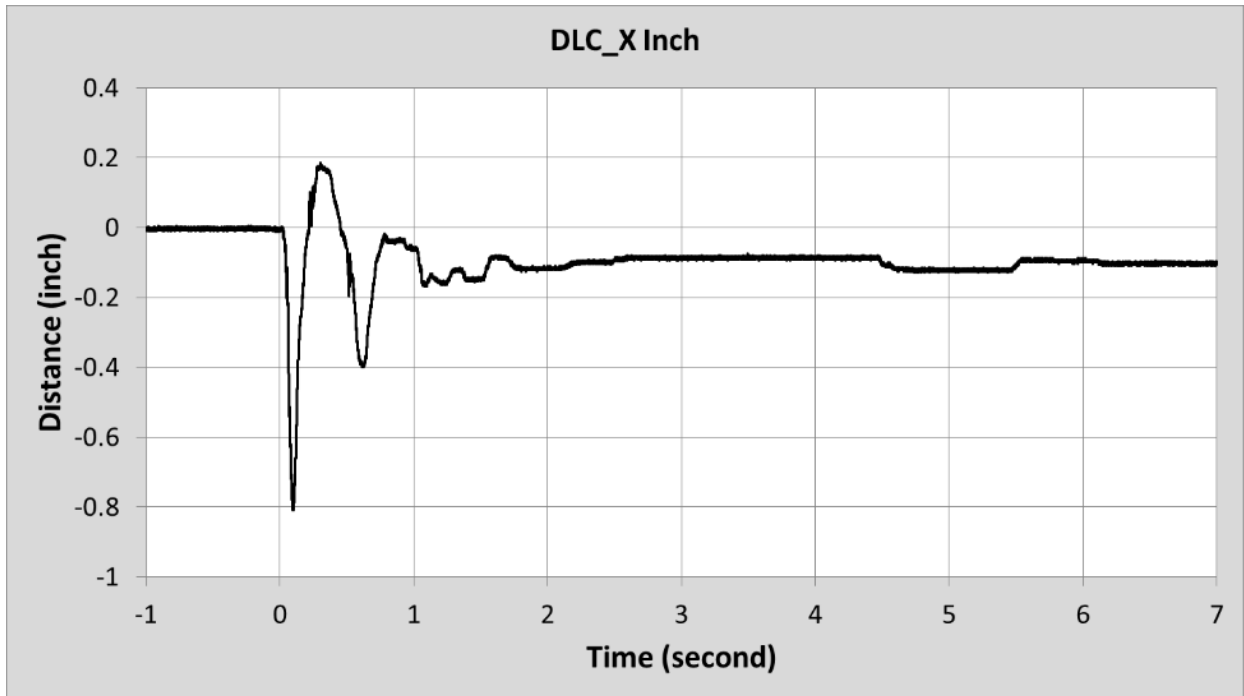


Figure D35. DLC_X String Potentiometer Data

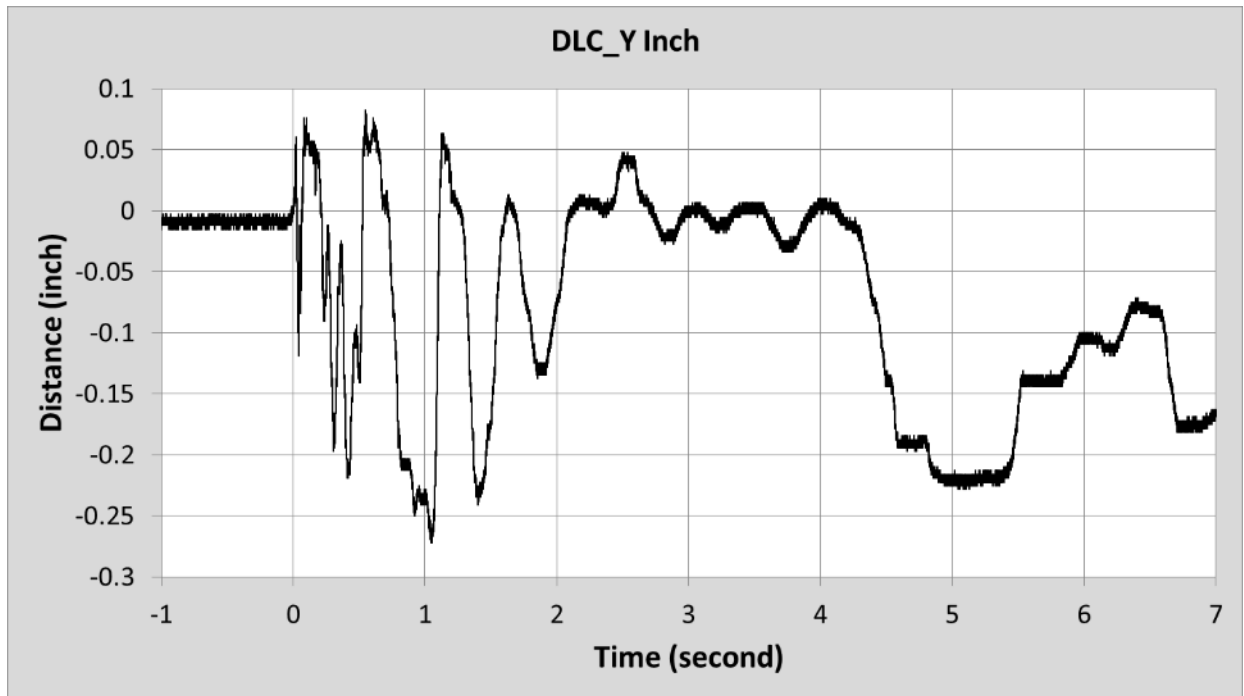


Figure D36. DLC_Y String Potentiometer Data

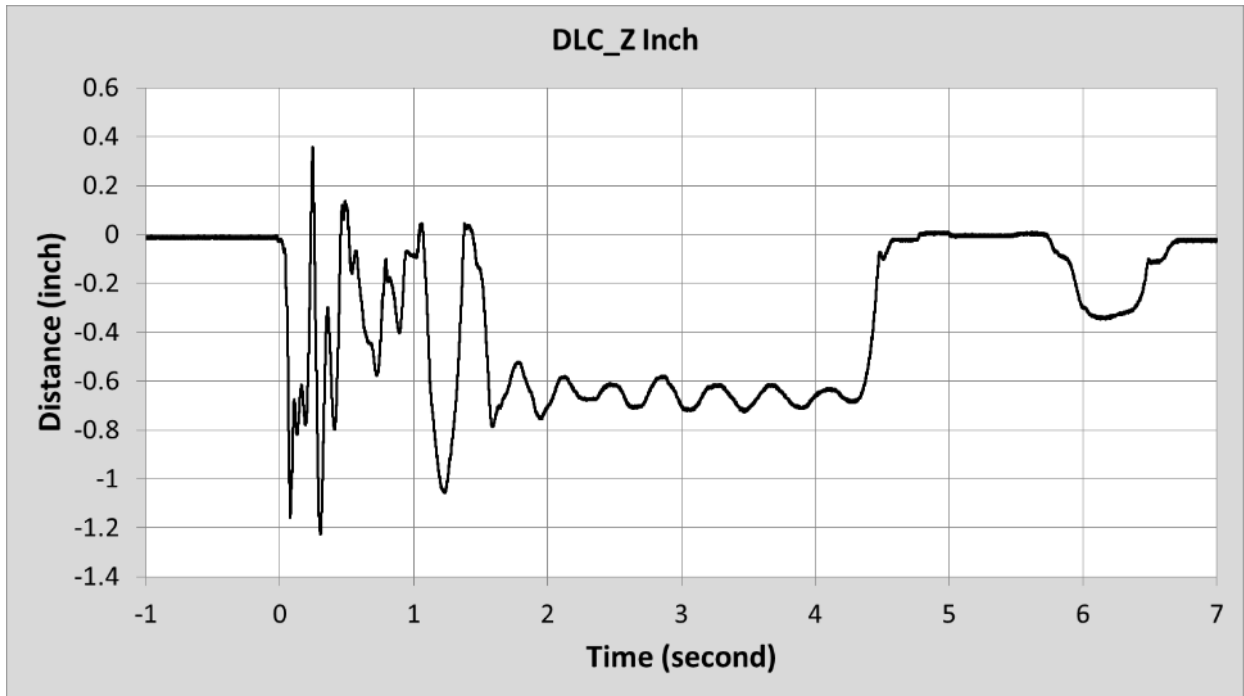


Figure D37. DLC_Z String Potentiometer Data

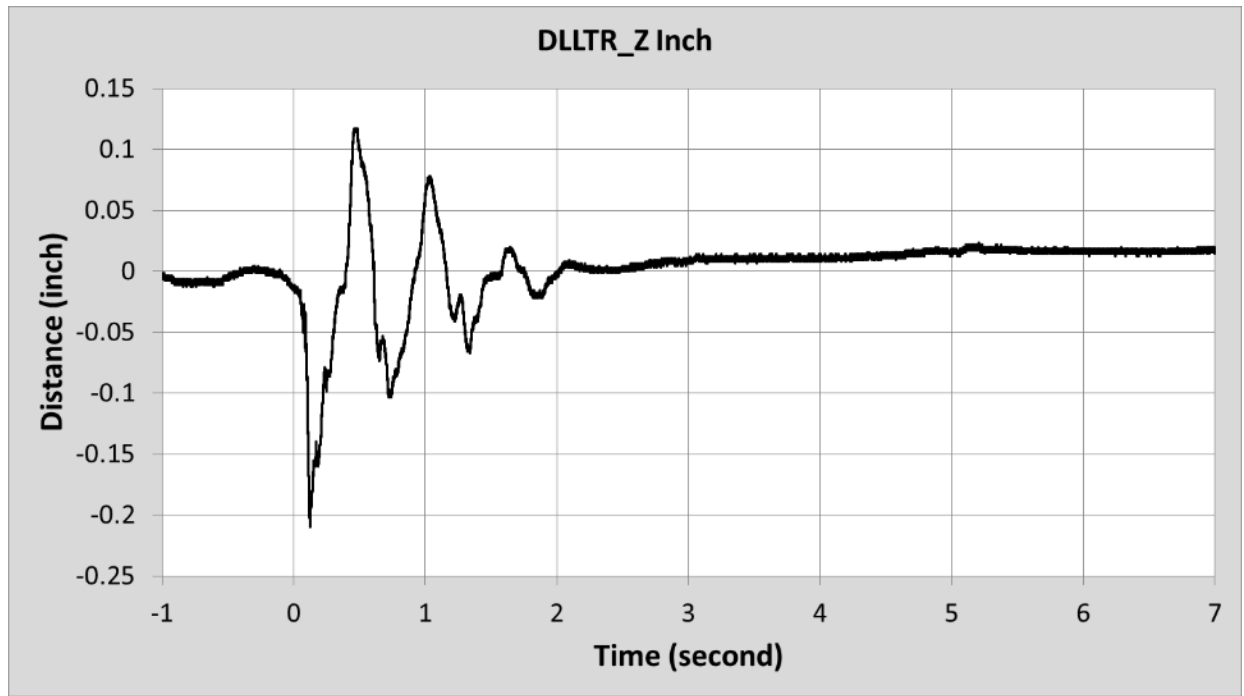


Figure D38. DLLTR_Z String Potentiometer Data

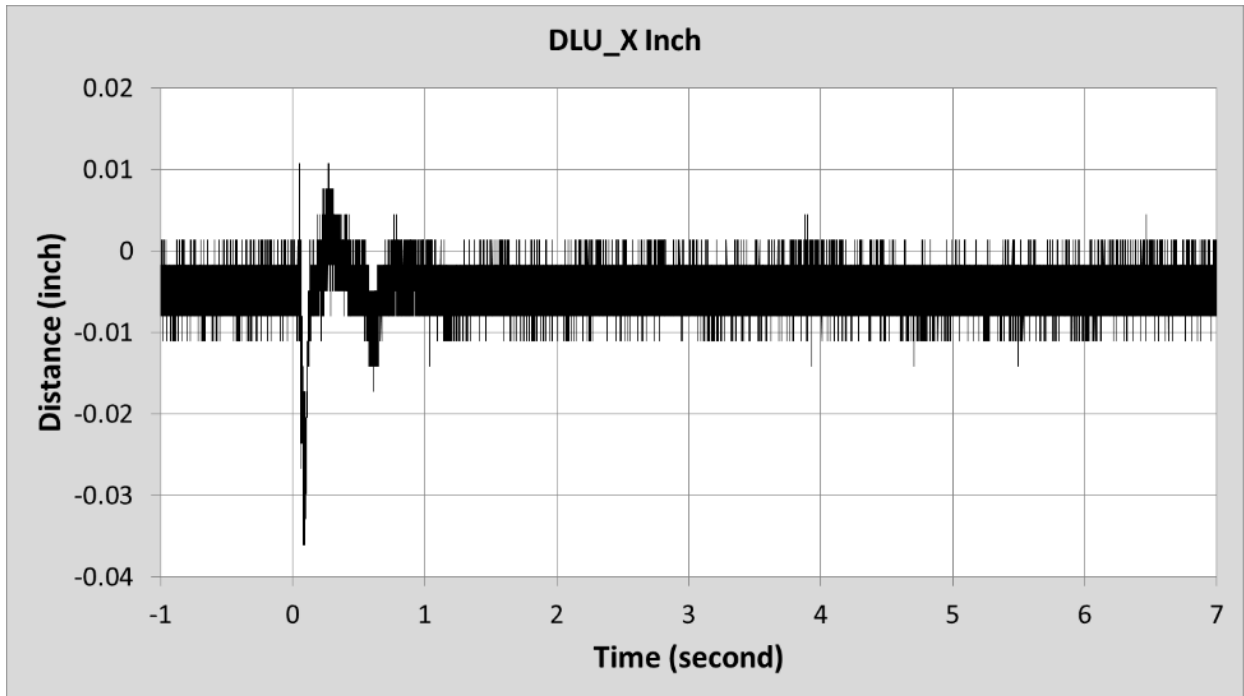


Figure D39. DLU_X String Potentiometer Data

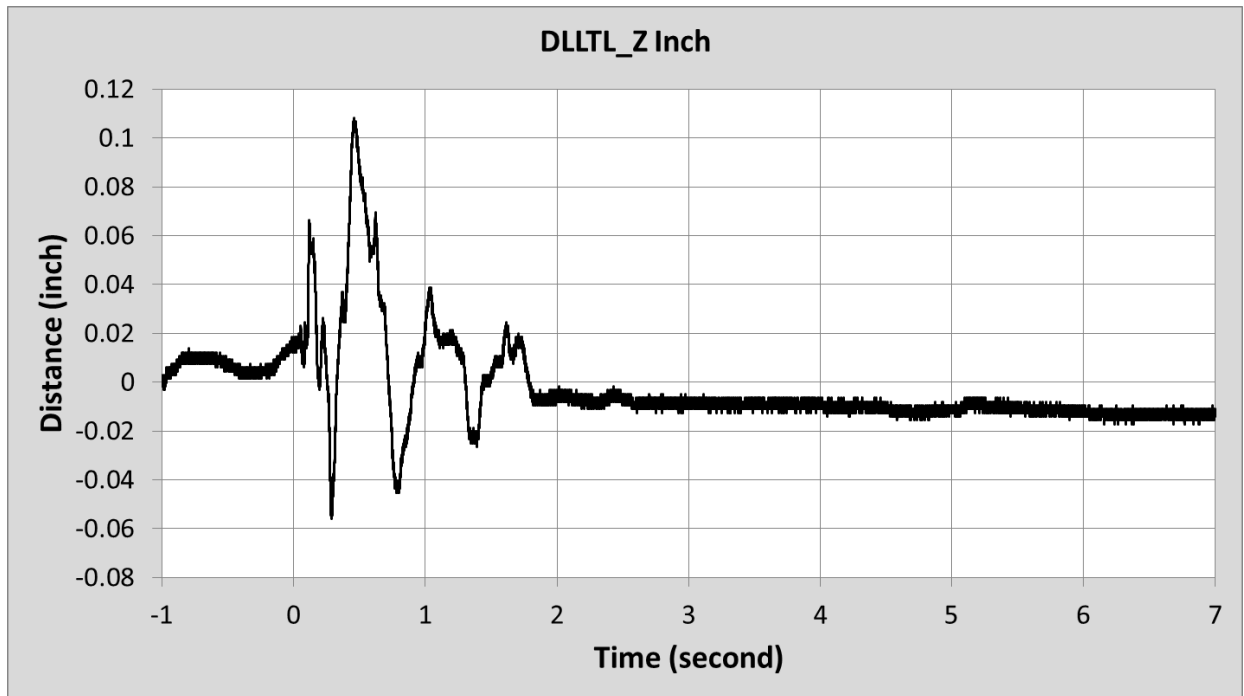


Figure D40. DLLTL_Z String Potentiometer Data

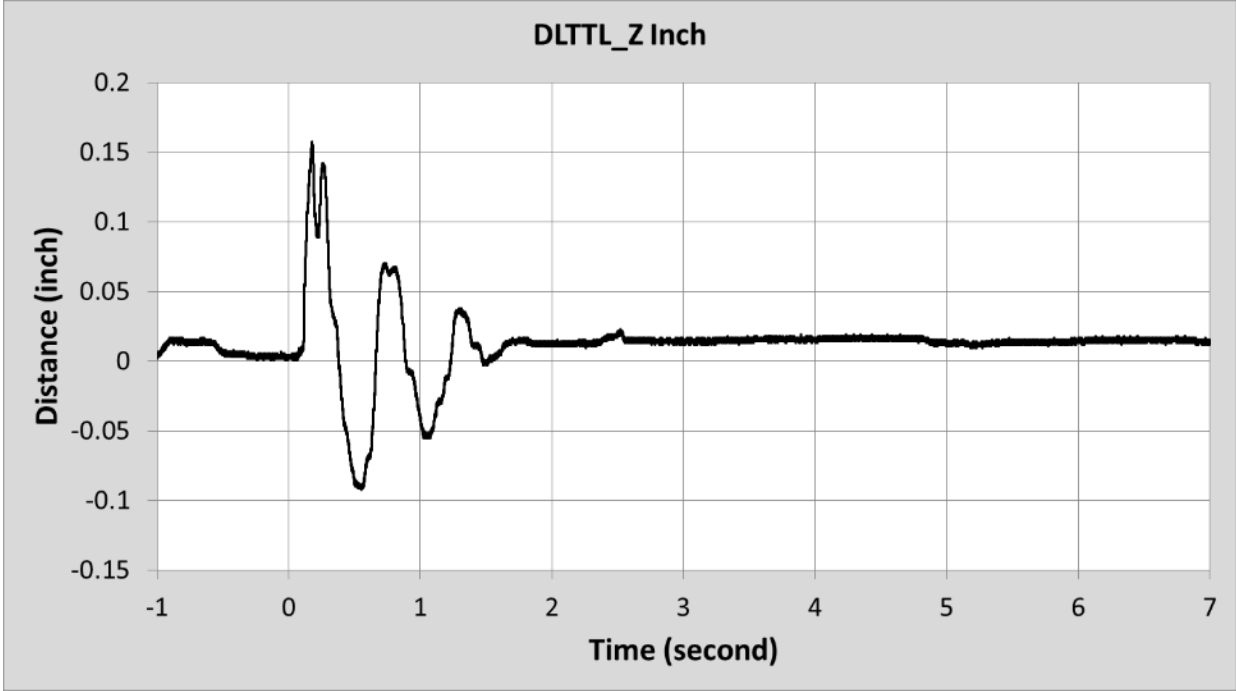


Figure D41. DLTTL_Z String Potentiometer Data

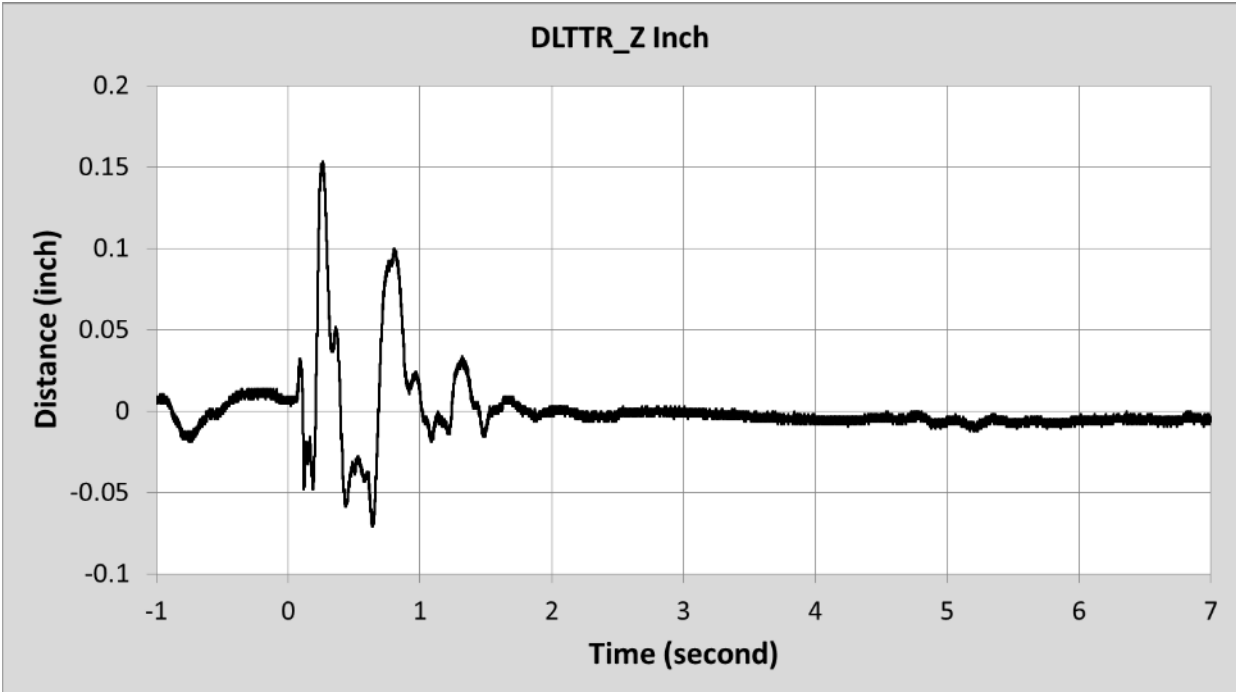


Figure D42. DLTTR_Z String Potentiometer Data

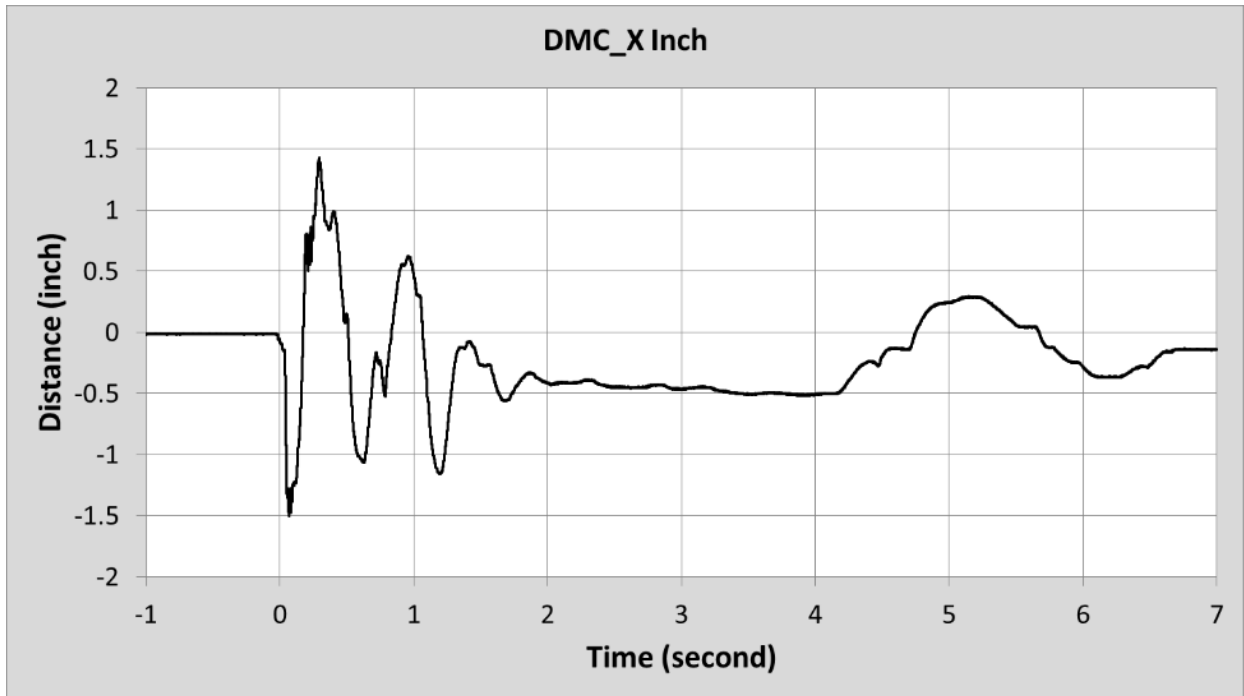


Figure D43. DMC_X String Potentiometer Data

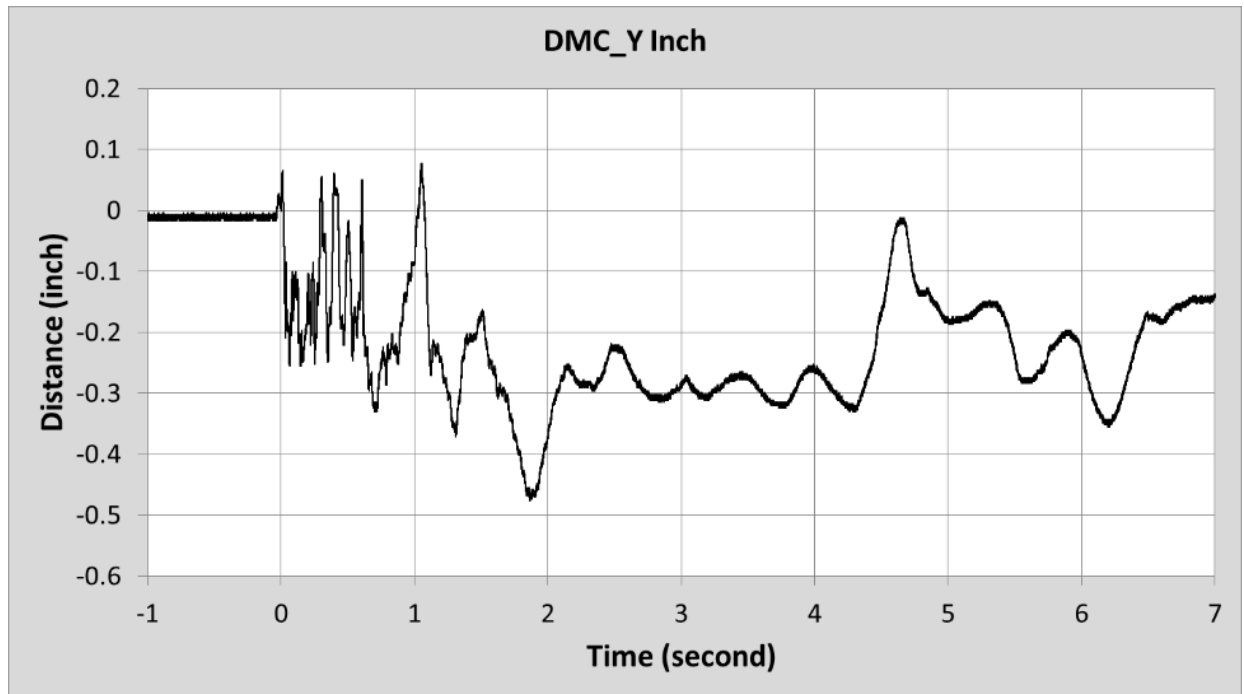


Figure D44. DMC_Y String Potentiometer Data

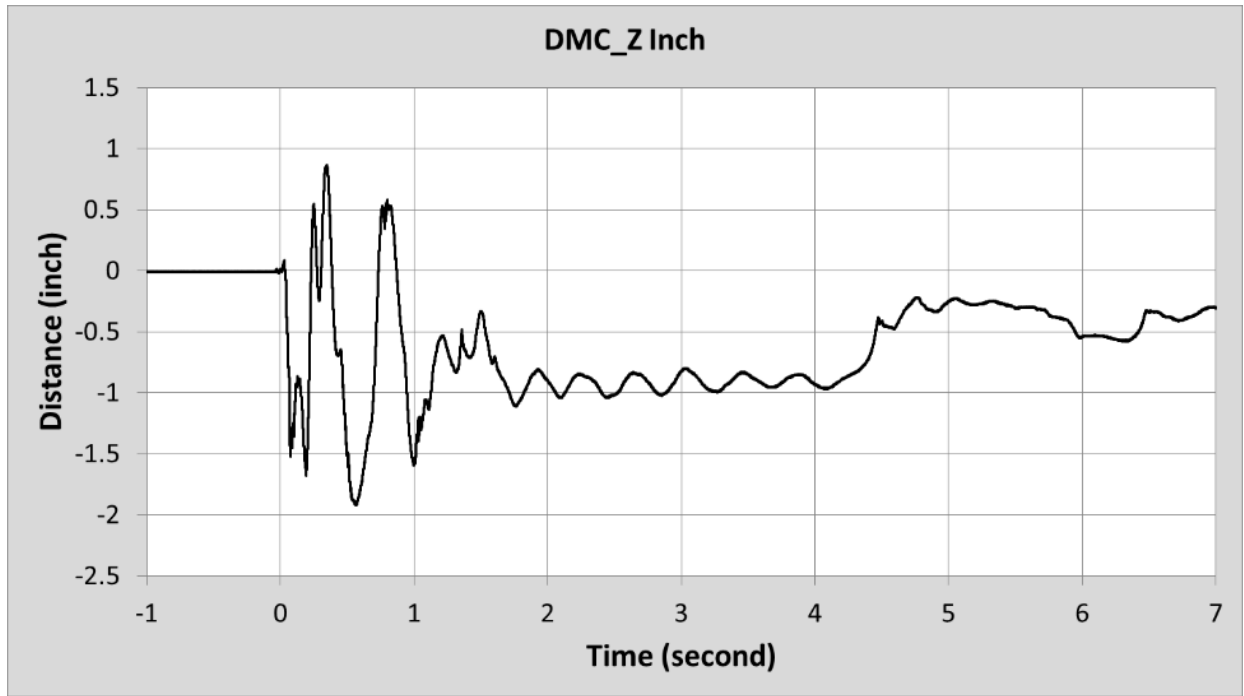


Figure D45. DMC_Z String Potentiometer Data

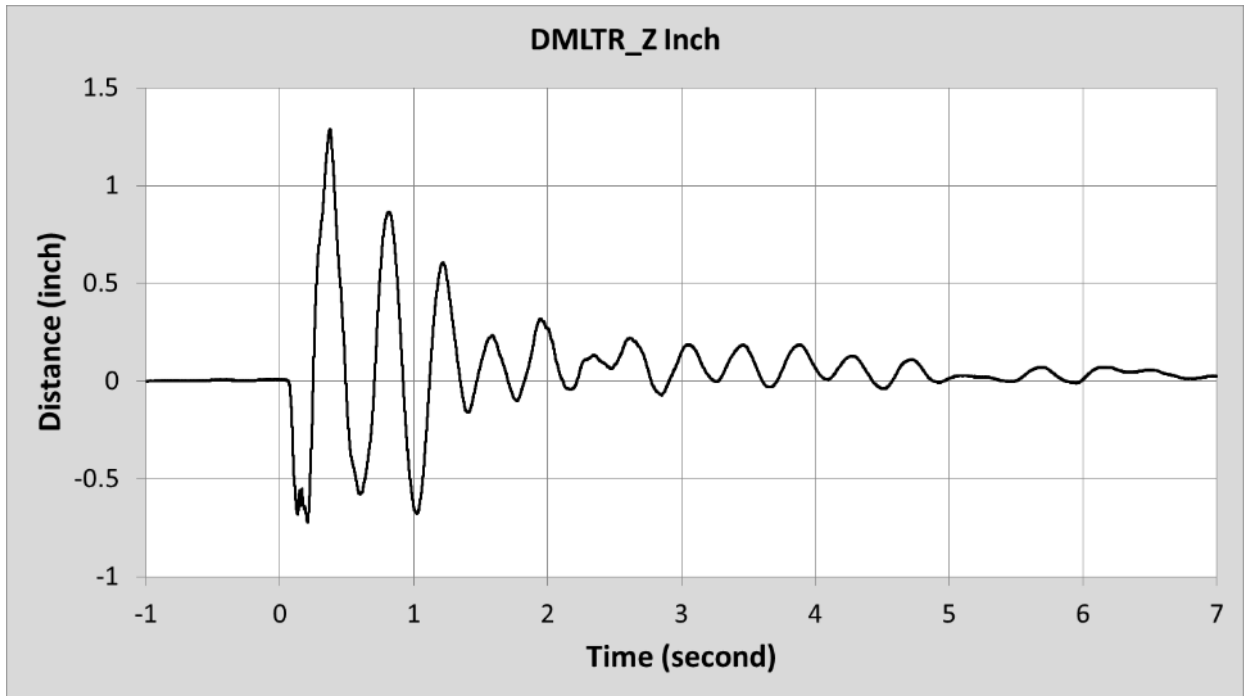


Figure D46. DMLTR_Z String Potentiometer Data

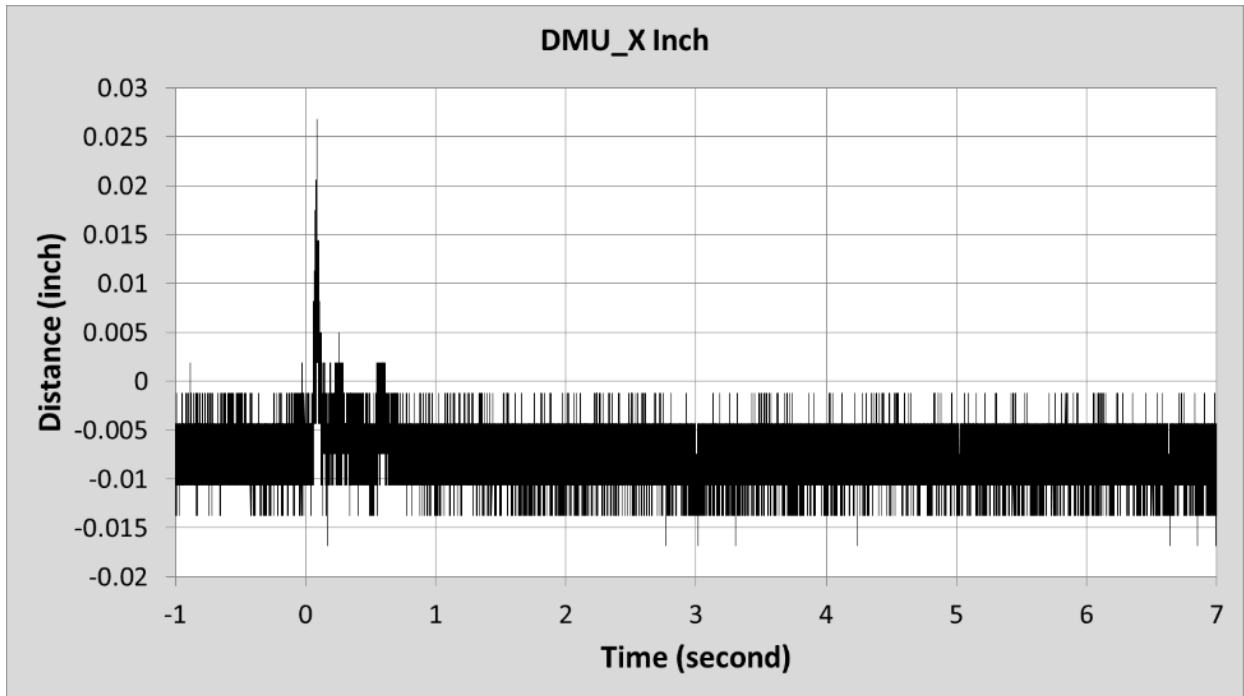


Figure D47. DMU_X String Potentiometer Data

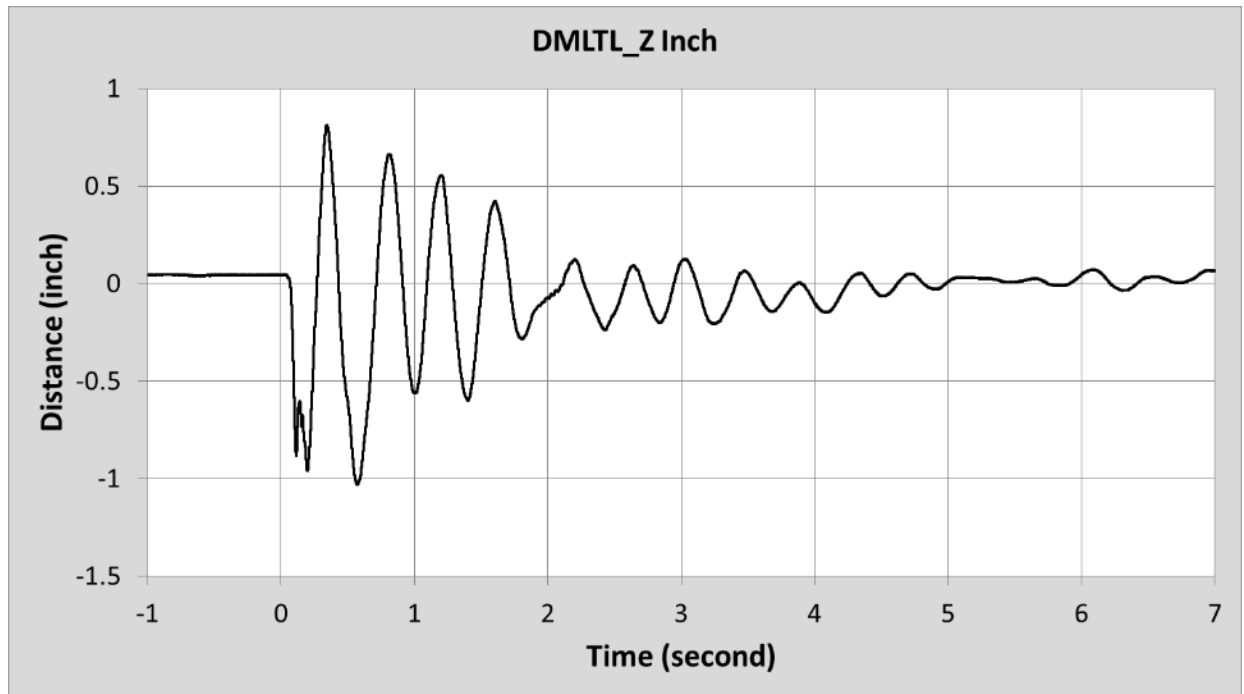


Figure D48. DMLTL_Z String Potentiometer Data

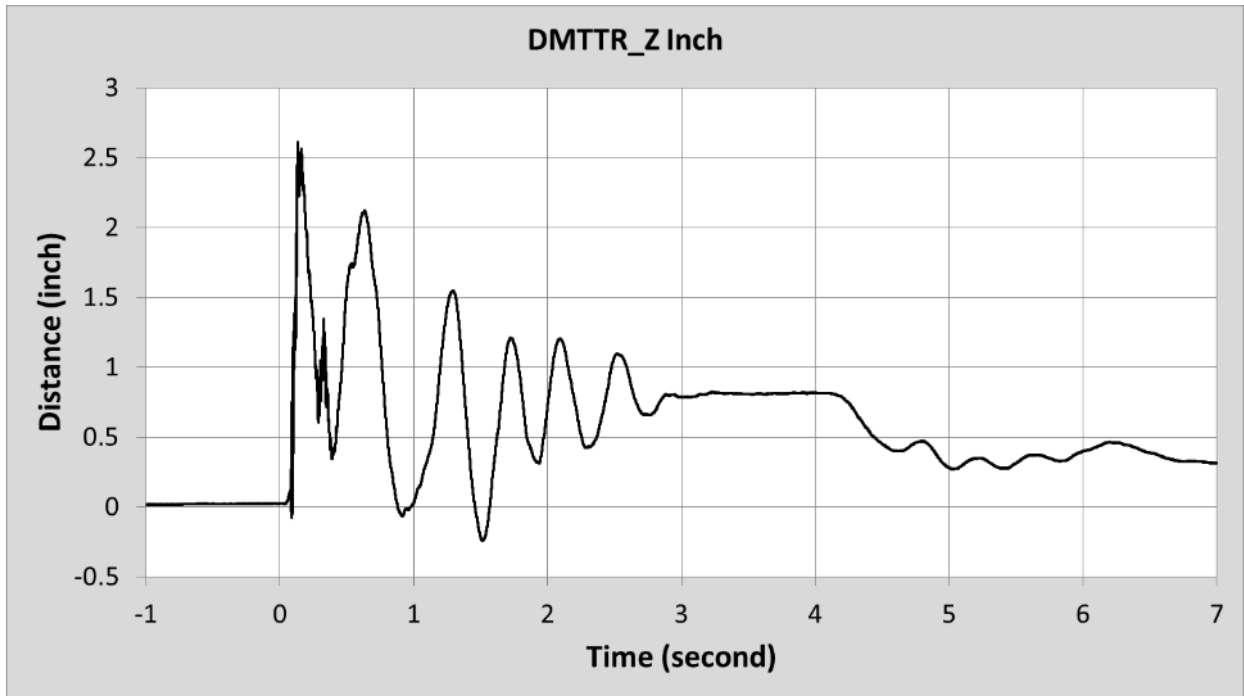


Figure D49. DMTTR_Z String Potentiometer Data

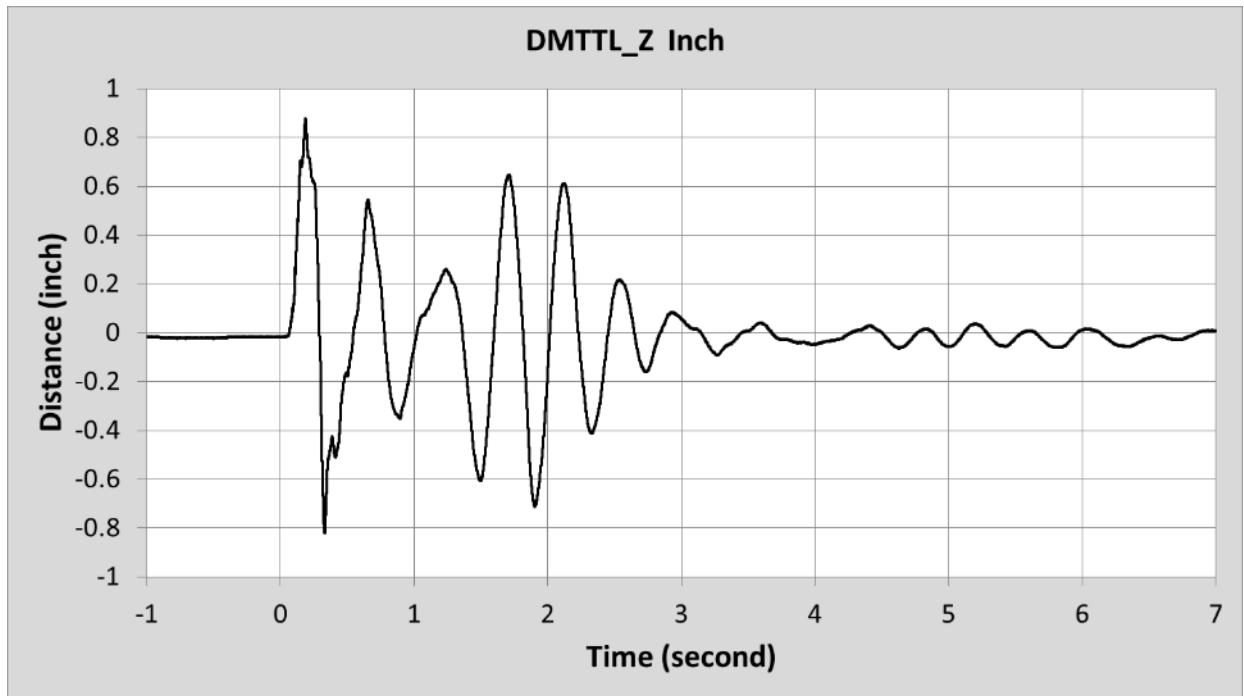


Figure D50. DMTTL_Z String Potentiometer Data

Appendix E. 8 mph Test Data

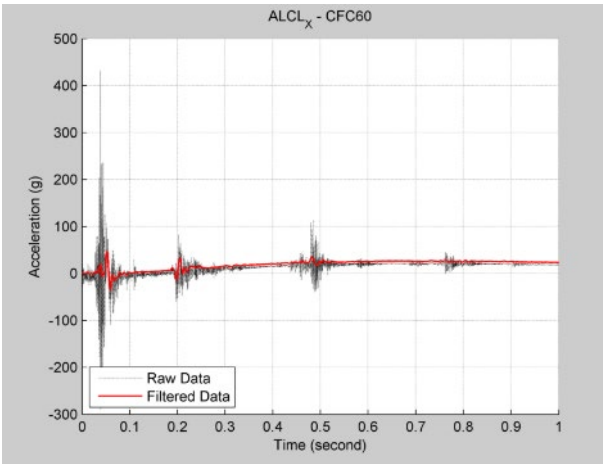


Figure E1. ALCL_X Accelerometer Data

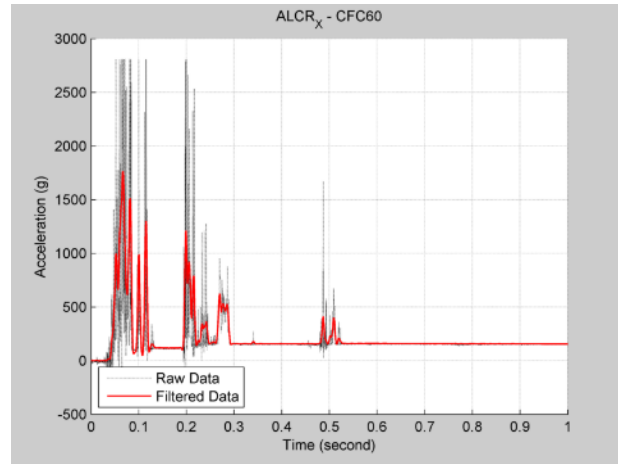


Figure E2. ALCR_X Accelerometer Data

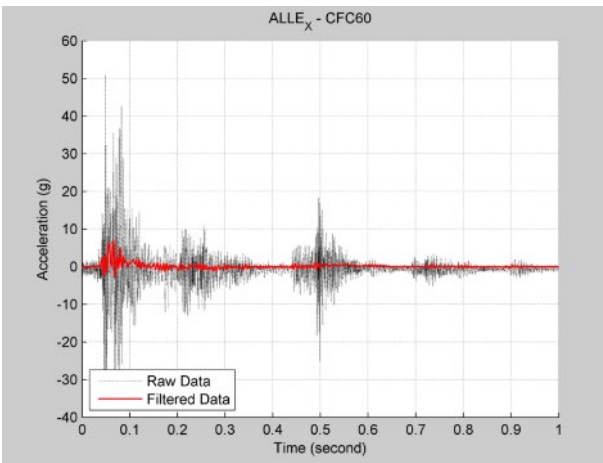


Figure E3. ALLE_X Accelerometer Data

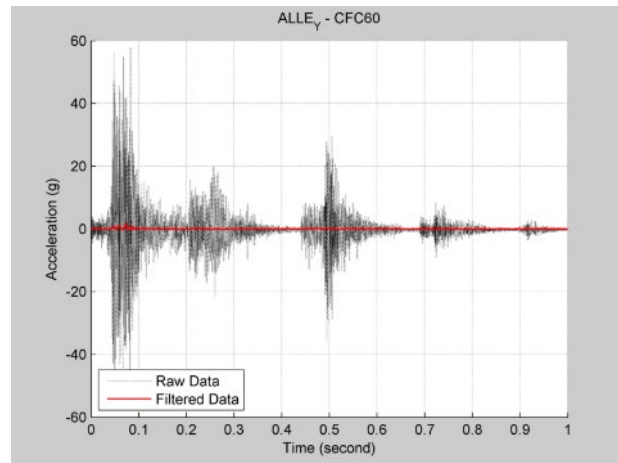


Figure E4. ALLE_Y Accelerometer Data

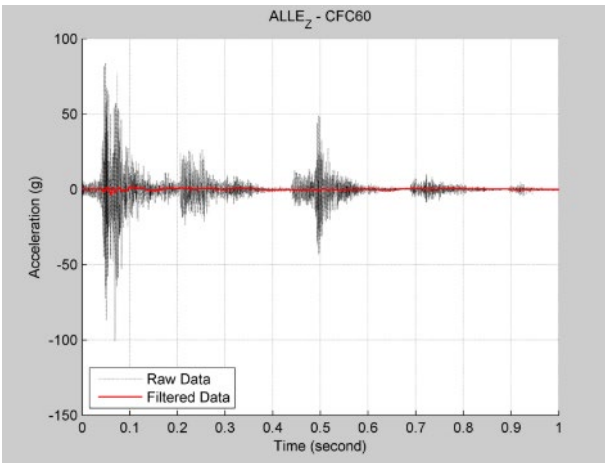


Figure E5. ALLE_Z Accelerometer Data

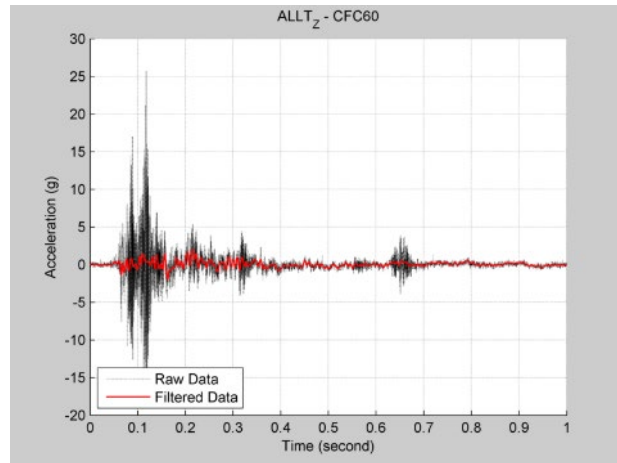


Figure E6. ALLT_Z Accelerometer Data

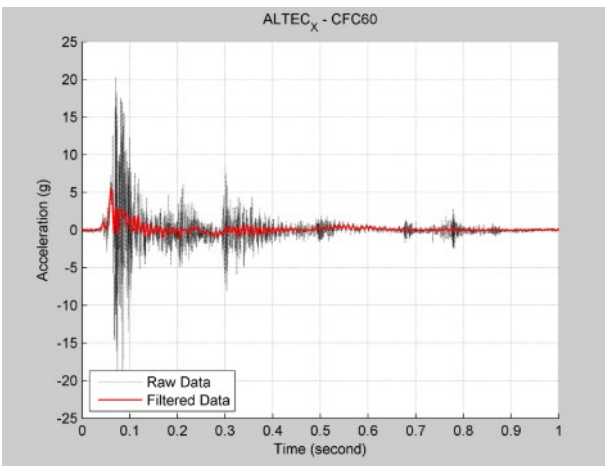


Figure E7. ALTEC_X Accelerometer Data

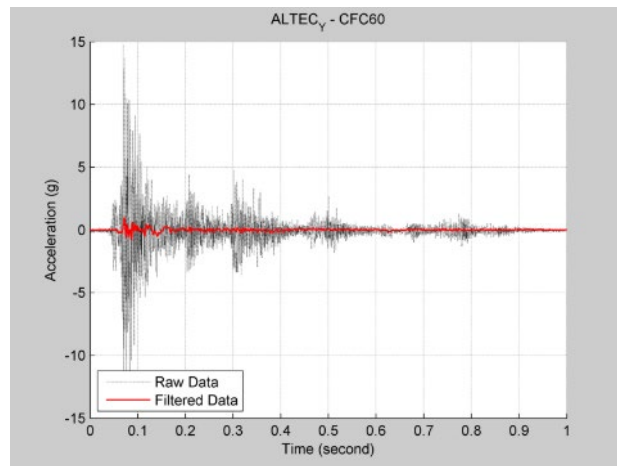


Figure E8. ALTEC_Y Accelerometer Data

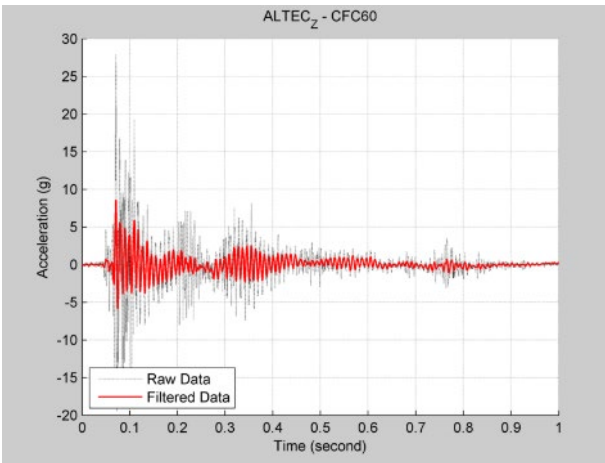


Figure E9. ALTEC_Z Accelerometer Data

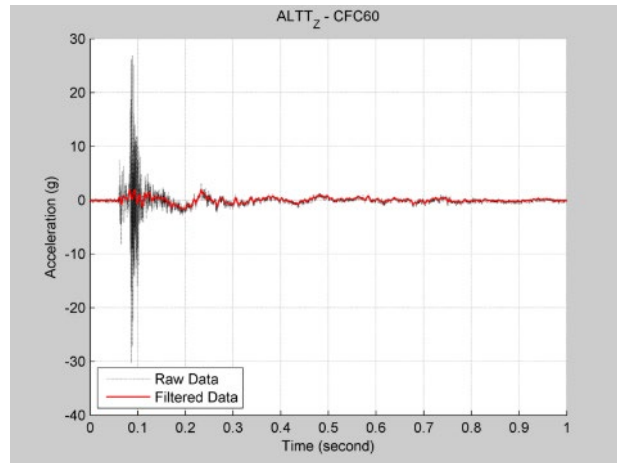


Figure E10. ALTT_Z Accelerometer Data

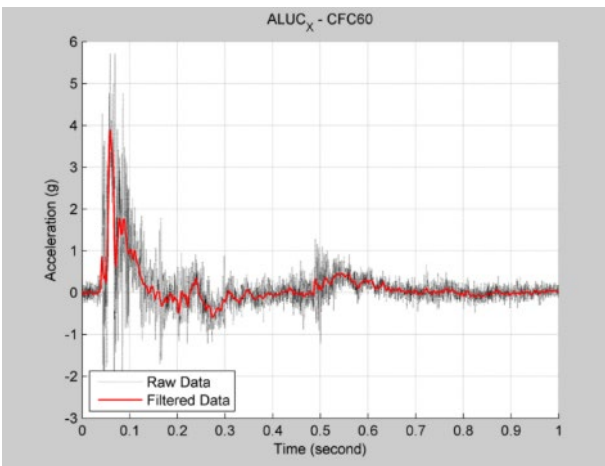


Figure E11. ALUC_X Accelerometer Data

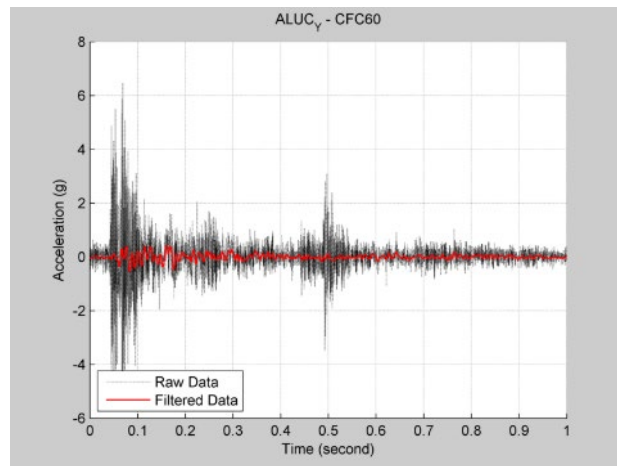


Figure E12. ALUC_Y Accelerometer Data

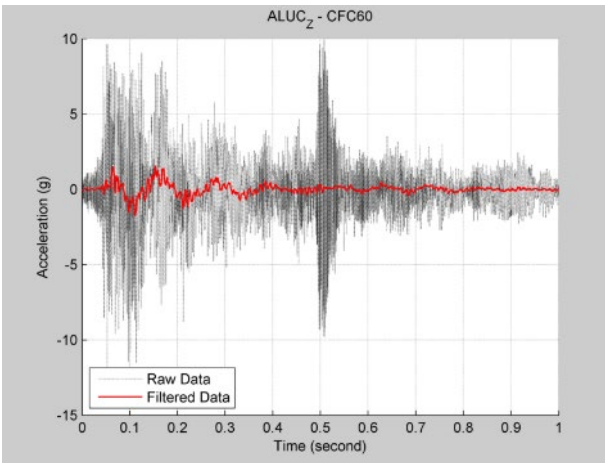


Figure E13. ALUC_Z Accelerometer Data

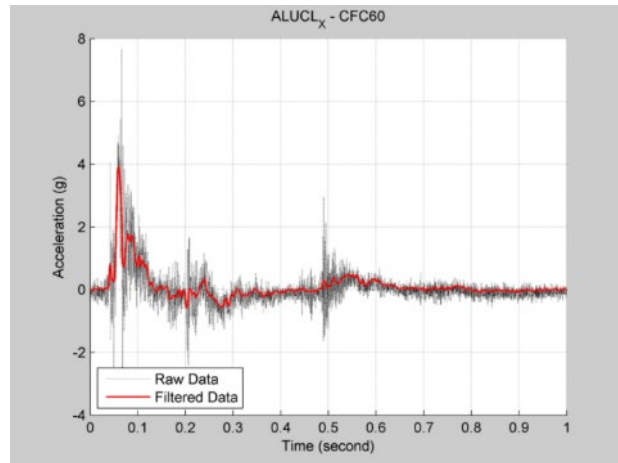


Figure E14. ALUCL_X Accelerometer Data

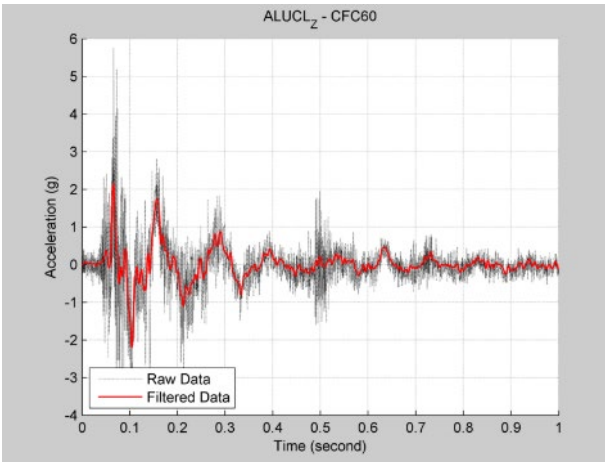


Figure E15. ALUCL_Z Accelerometer Data

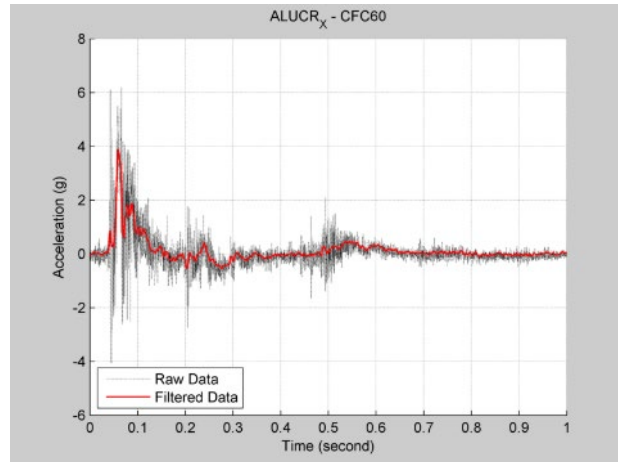


Figure E16. ALUCR_X Accelerometer Data

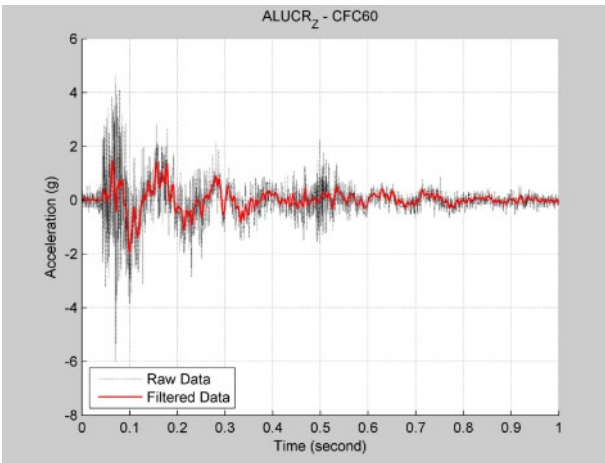


Figure E17. ALUCR_Z Accelerometer Data

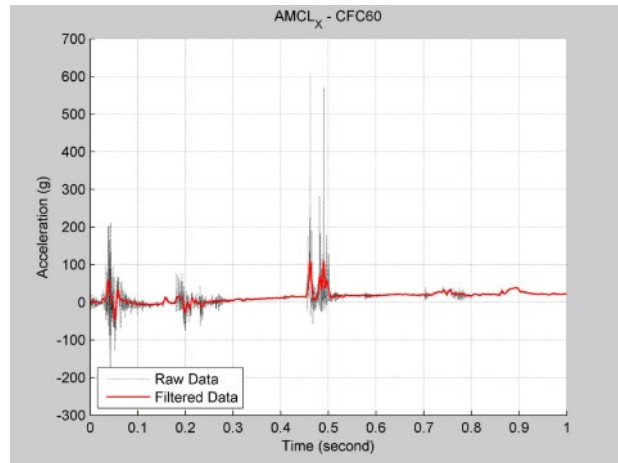


Figure E18. AMCL_X Accelerometer Data

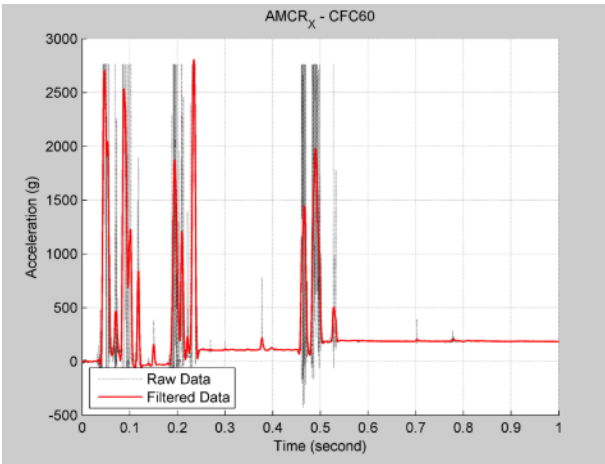


Figure E19. AMCR_X Accelerometer Data

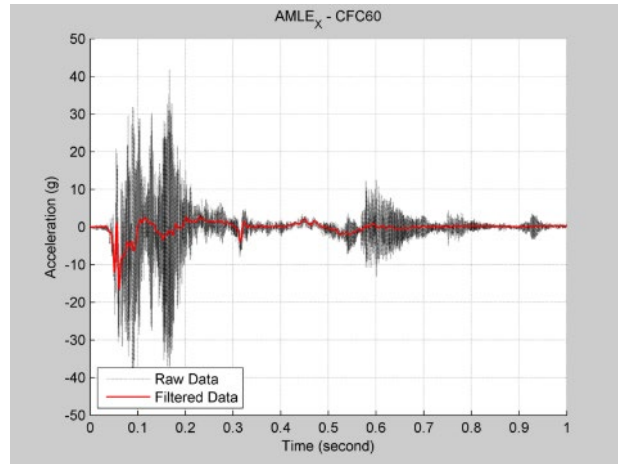


Figure E20. AMLE_X Accelerometer Data

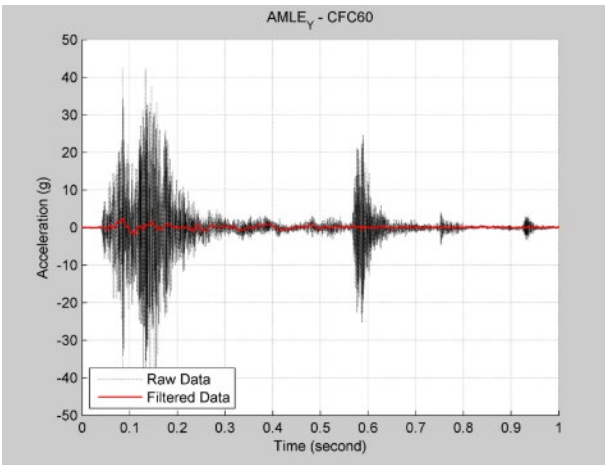


Figure E21. AMLE_Y Accelerometer Data

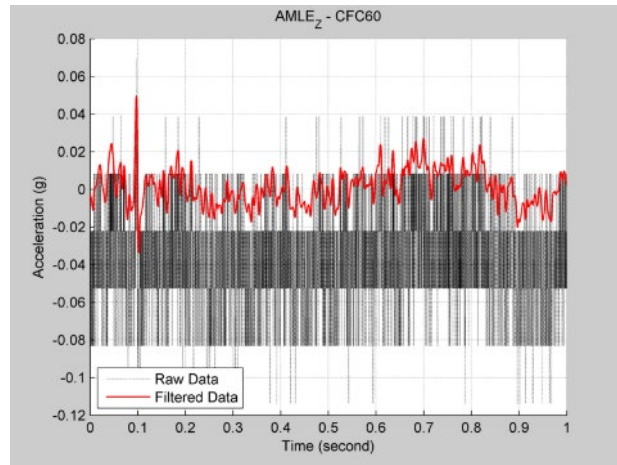


Figure E22. AMLE_Z Accelerometer Data

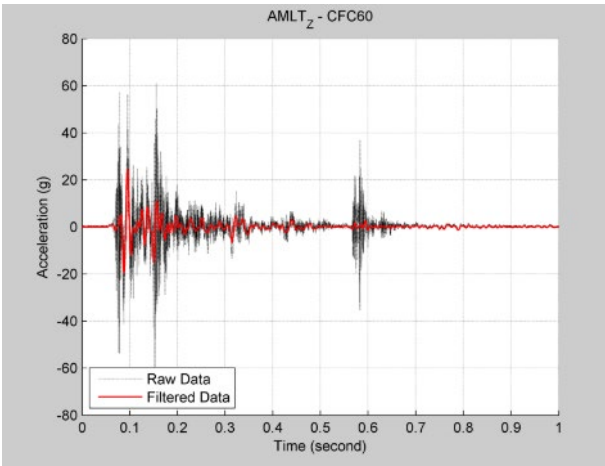


Figure E23. AMLT_Z Accelerometer Data

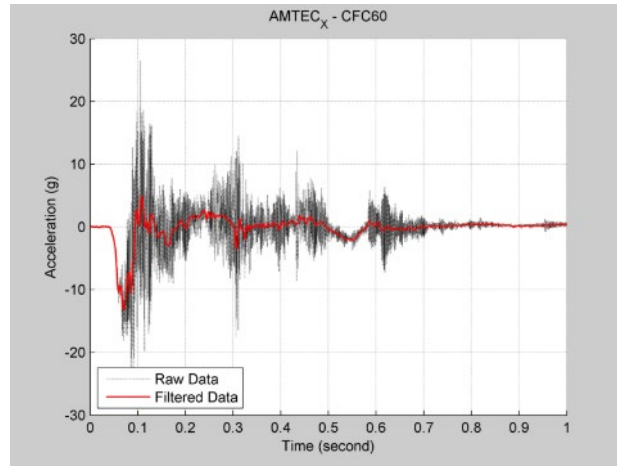


Figure E24. AMTEC_X Accelerometer Data

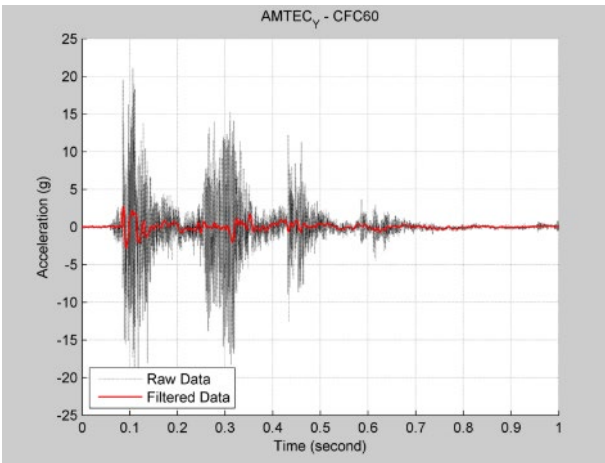


Figure E25. AMTEC_Y Accelerometer Data

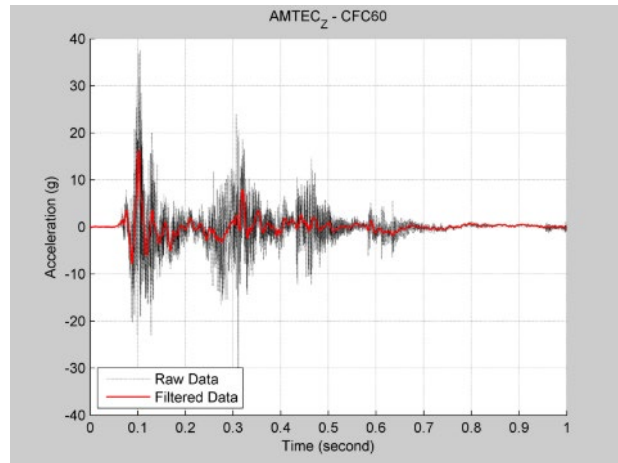


Figure E26. AMTEC_Z Accelerometer Data

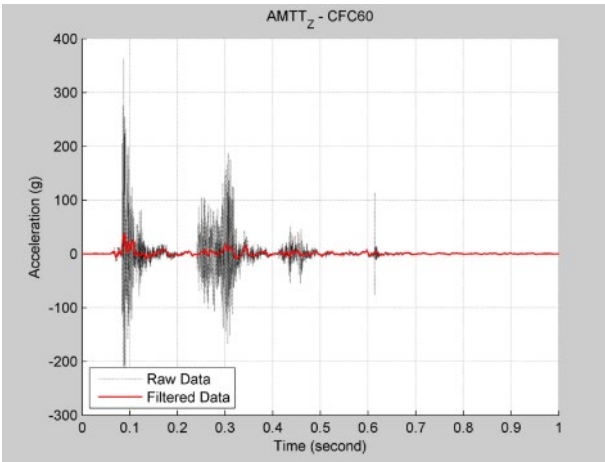


Figure E27. AMTT_Z Accelerometer Data

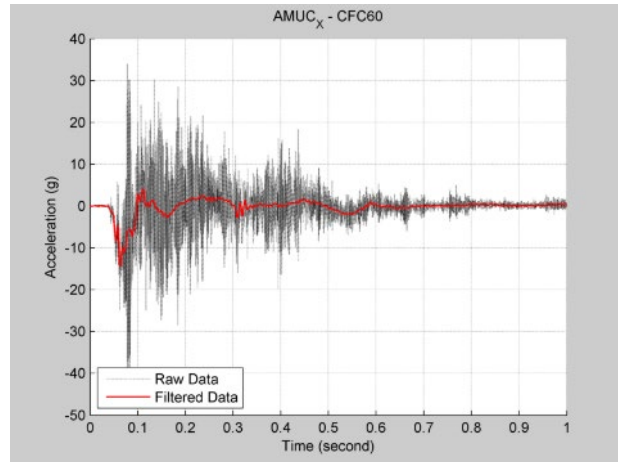


Figure E28. AMUC_X Accelerometer Data

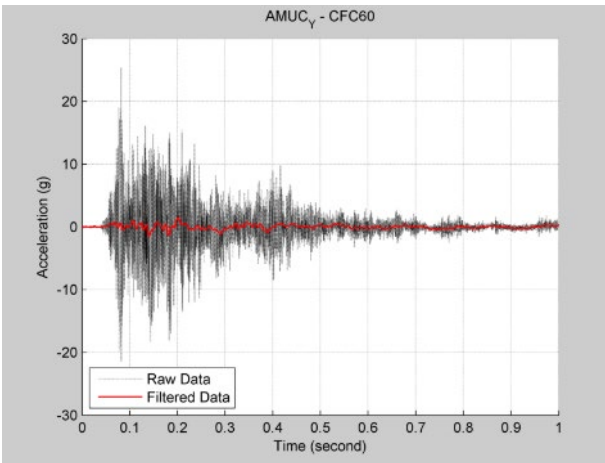


Figure E29. AMUC_Y Accelerometer Data

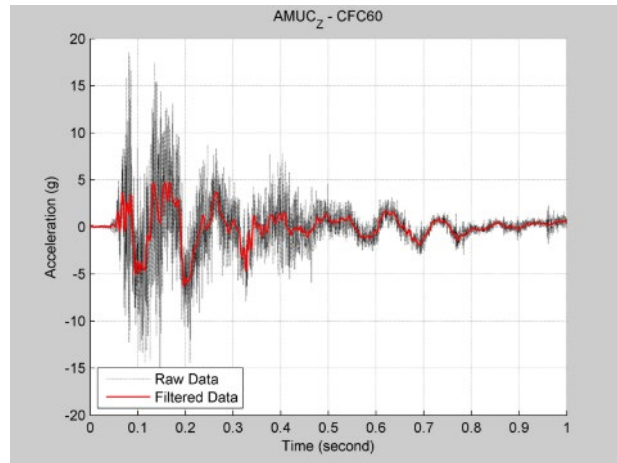


Figure E30. AMUC_Z Accelerometer Data

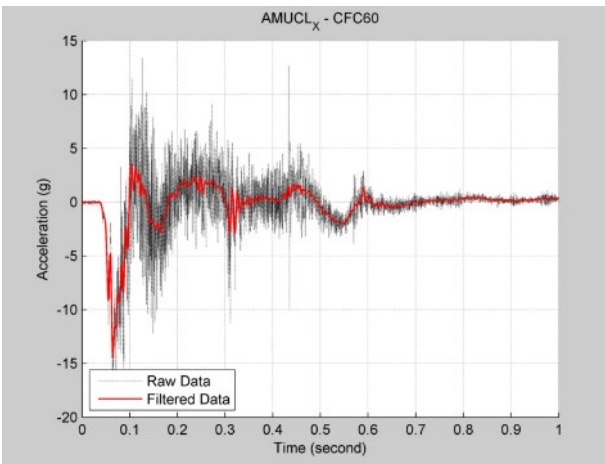


Figure E31. AMUCL_X Accelerometer Data

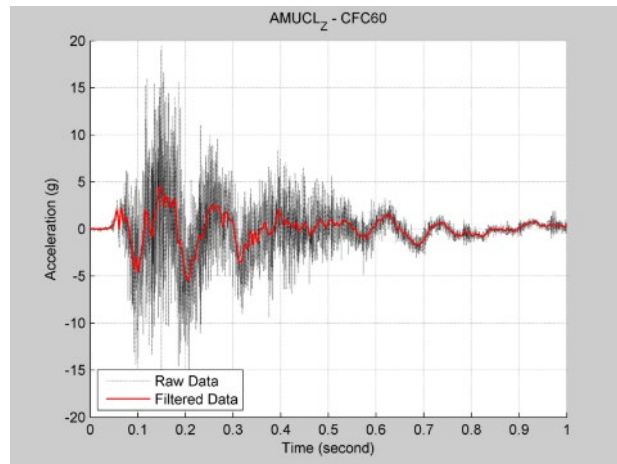


Figure E32. AMUCL_Z Accelerometer Data

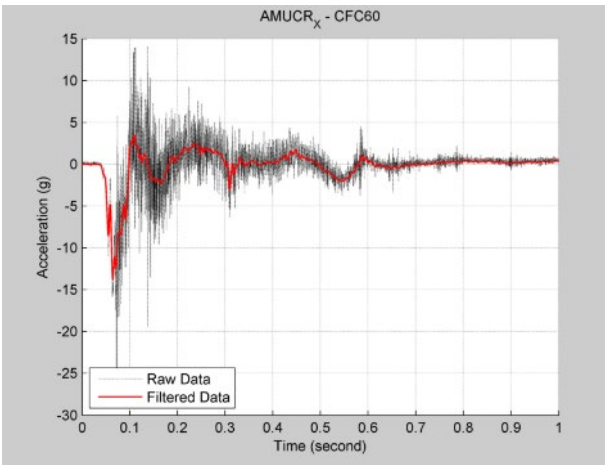


Figure E33. AMUCR_X Accelerometer Data

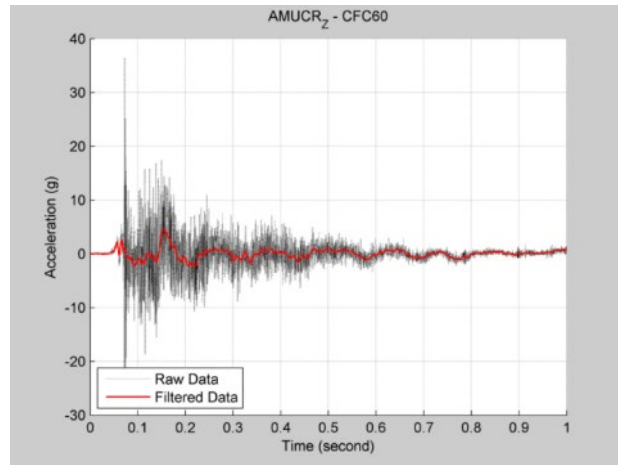


Figure E34. AMUCR_Z Accelerometer Data

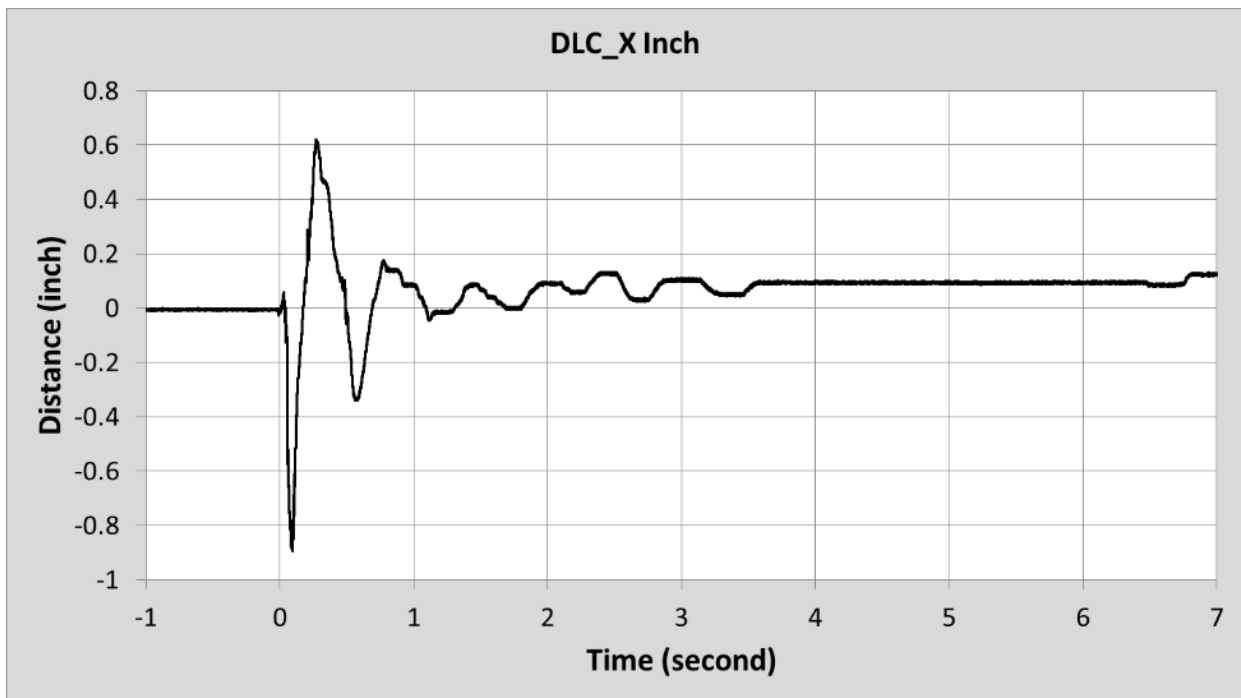


Figure E35. DLC_X String Potentiometer Data

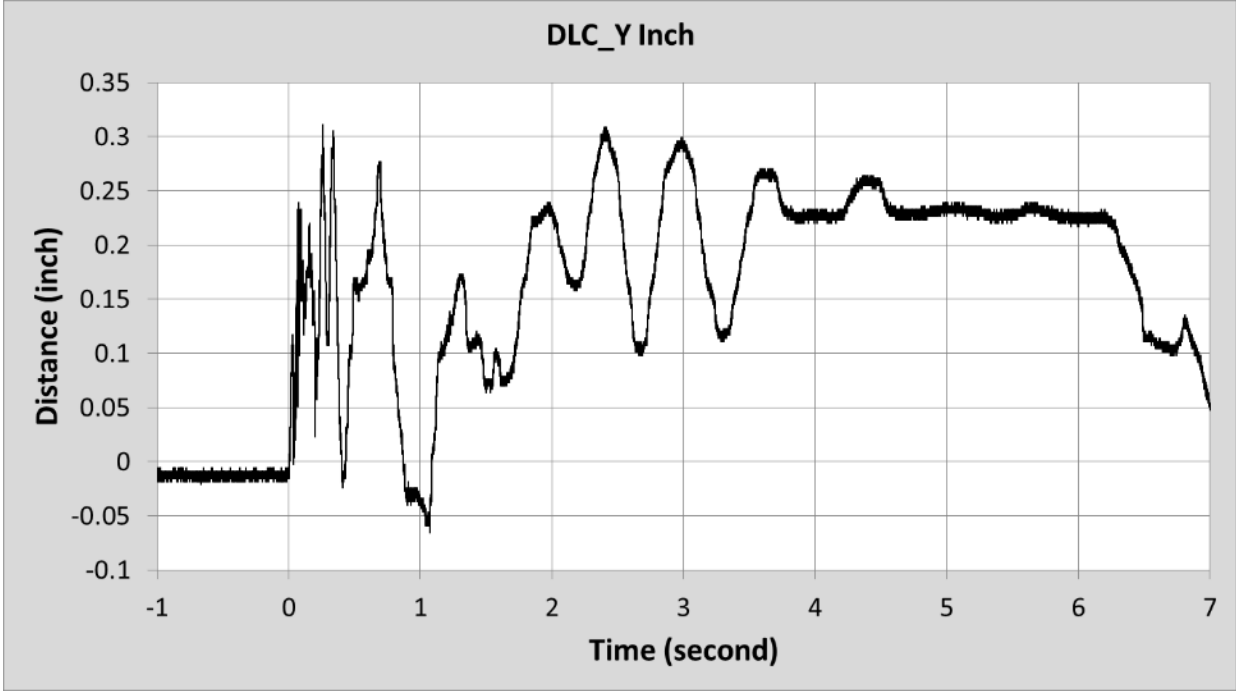


Figure E36. DLC_Y String Potentiometer Data

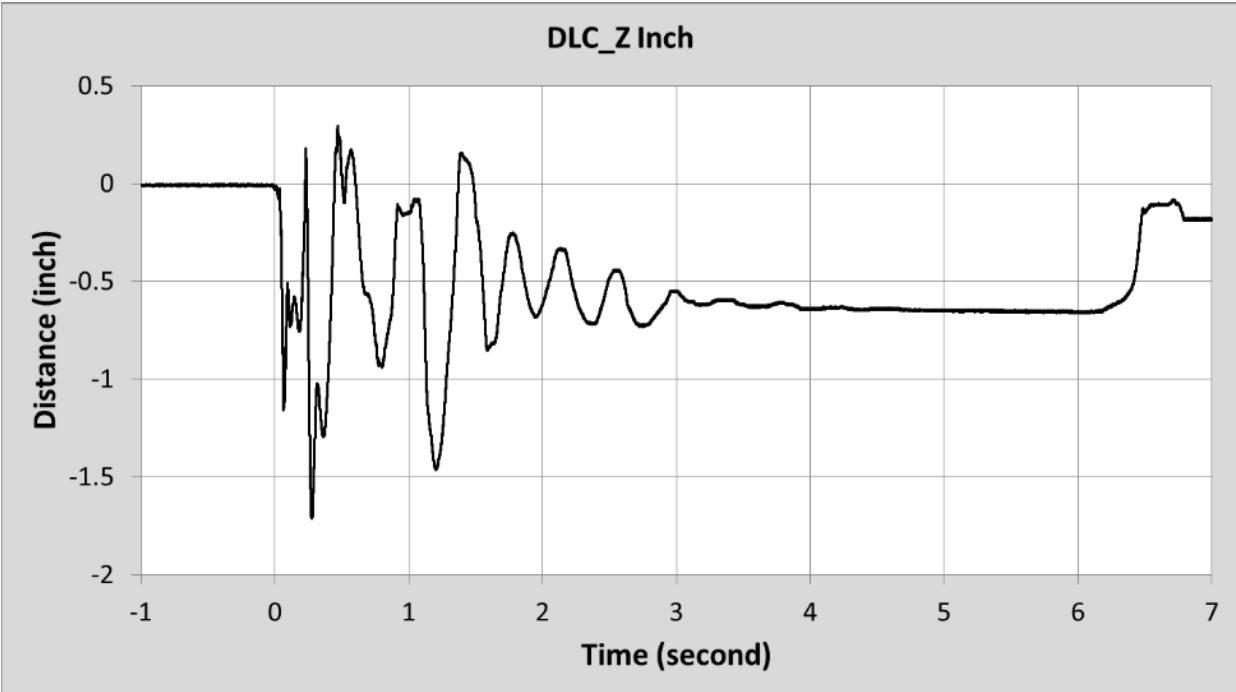


Figure E37. DLC_Z String Potentiometer Data

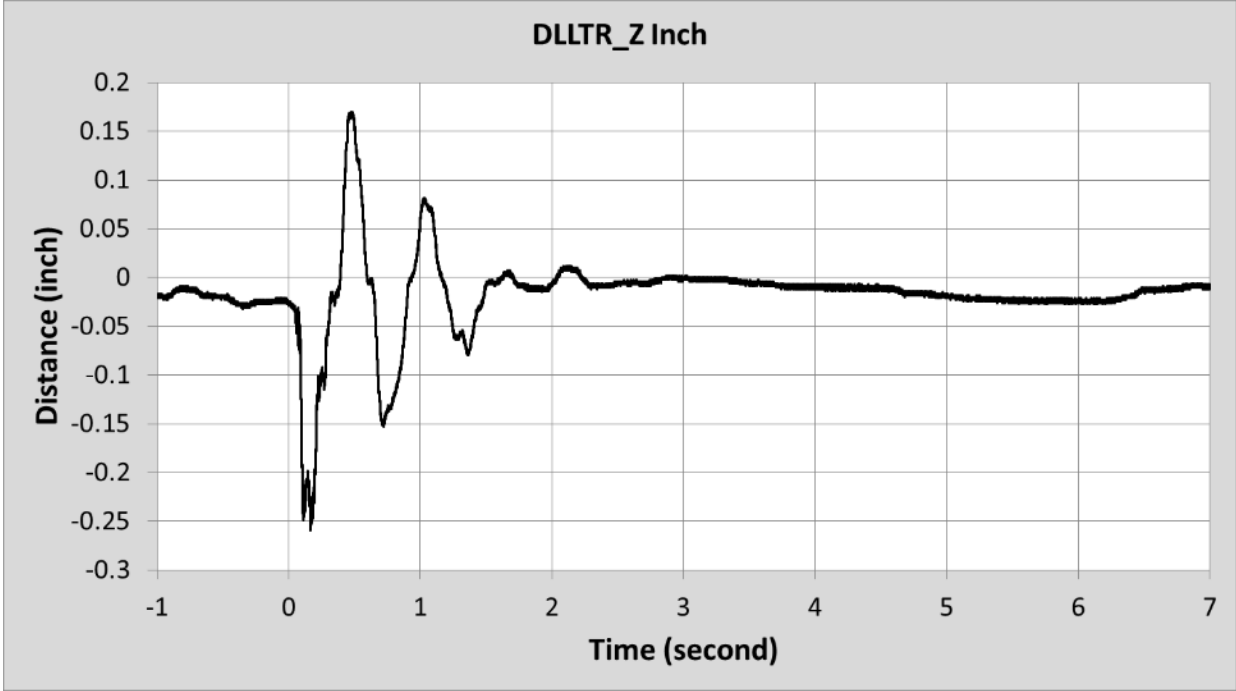


Figure E38. DLLTR_Z String Potentiometer Data

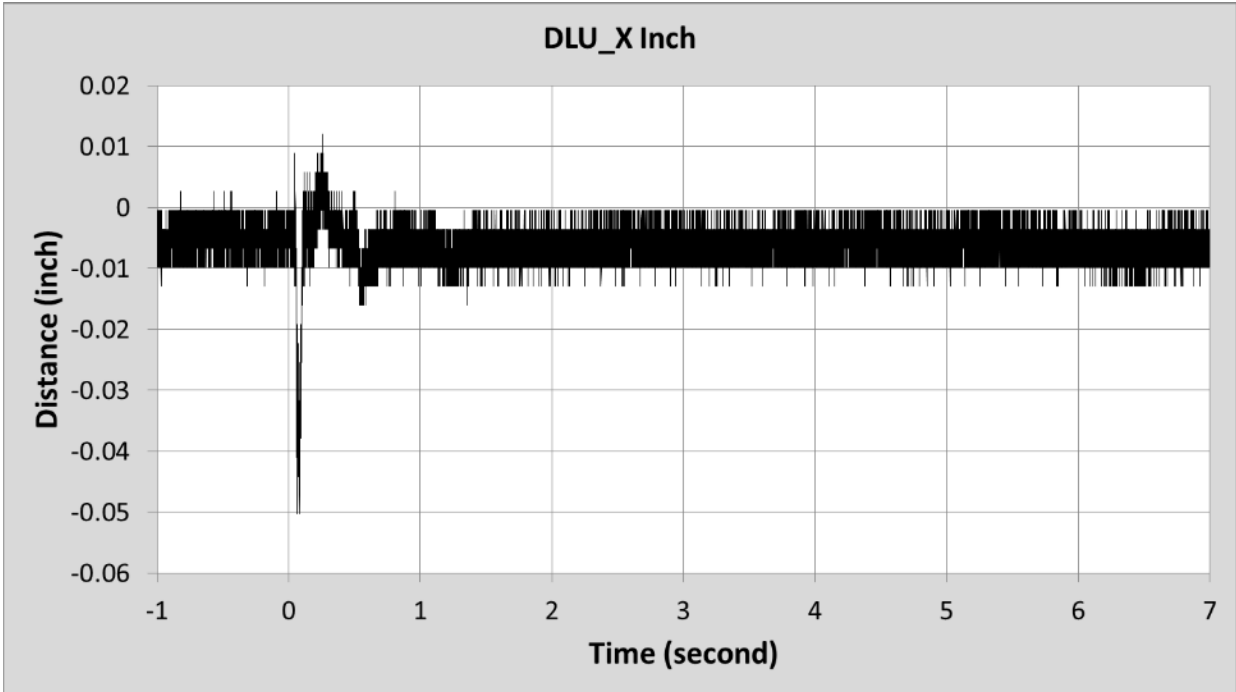


Figure E39. DLU_X String Potentiometer Data

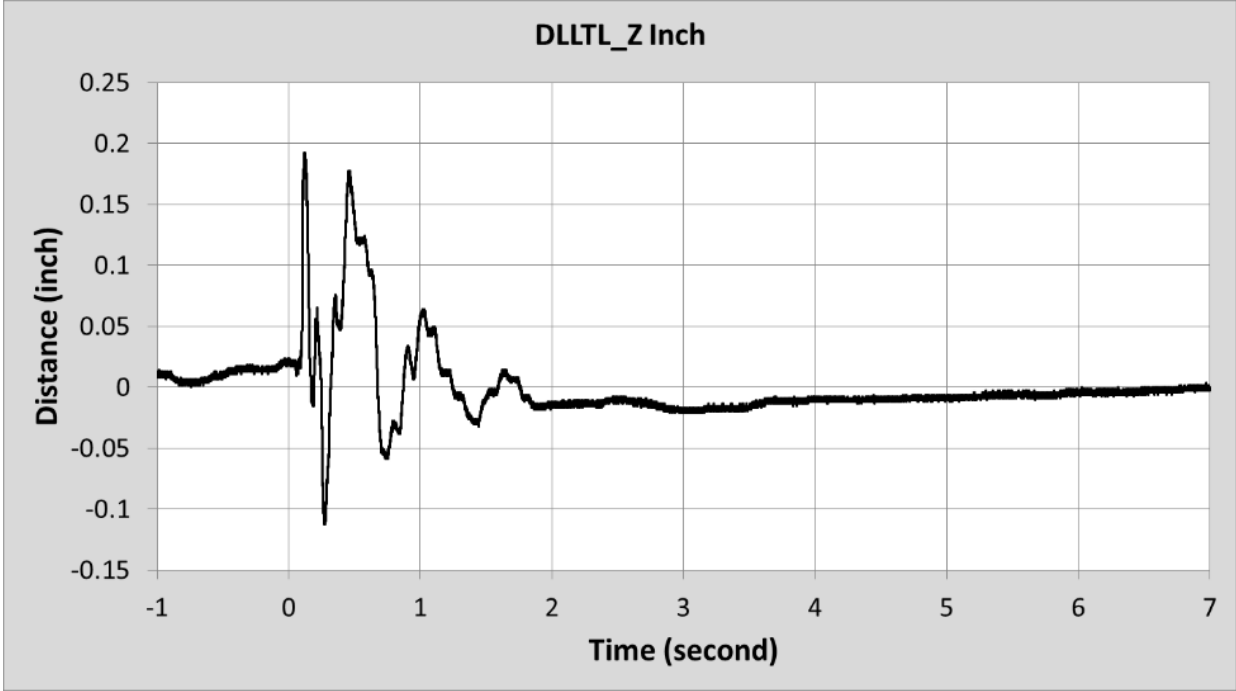


Figure E40. DLLTL_Z String Potentiometer Data

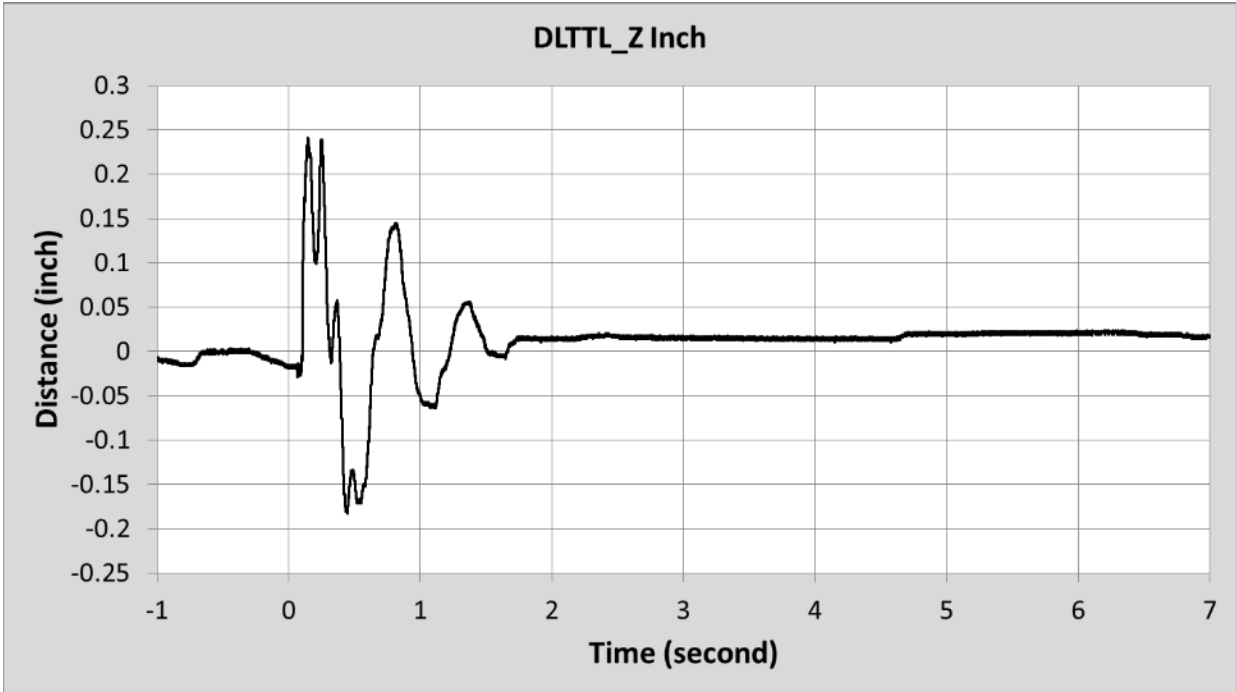


Figure E41. DLTTL_Z String Potentiometer Data

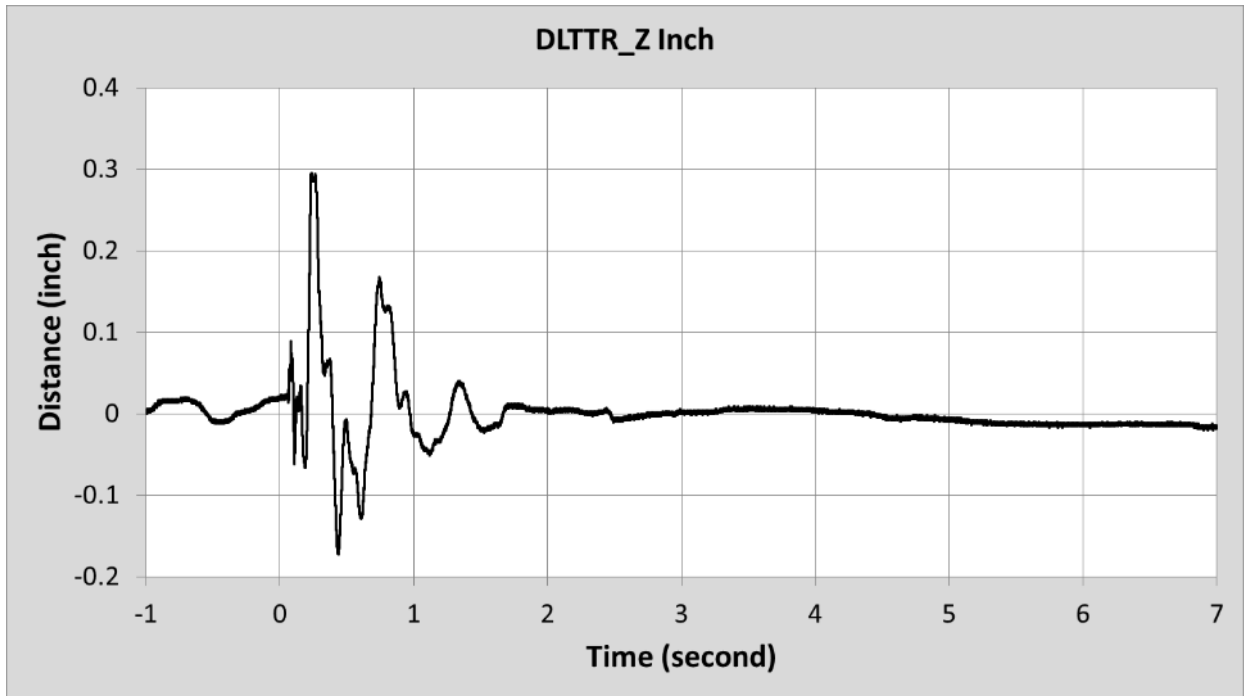


Figure E42. DLTTR_Z String Potentiometer Data

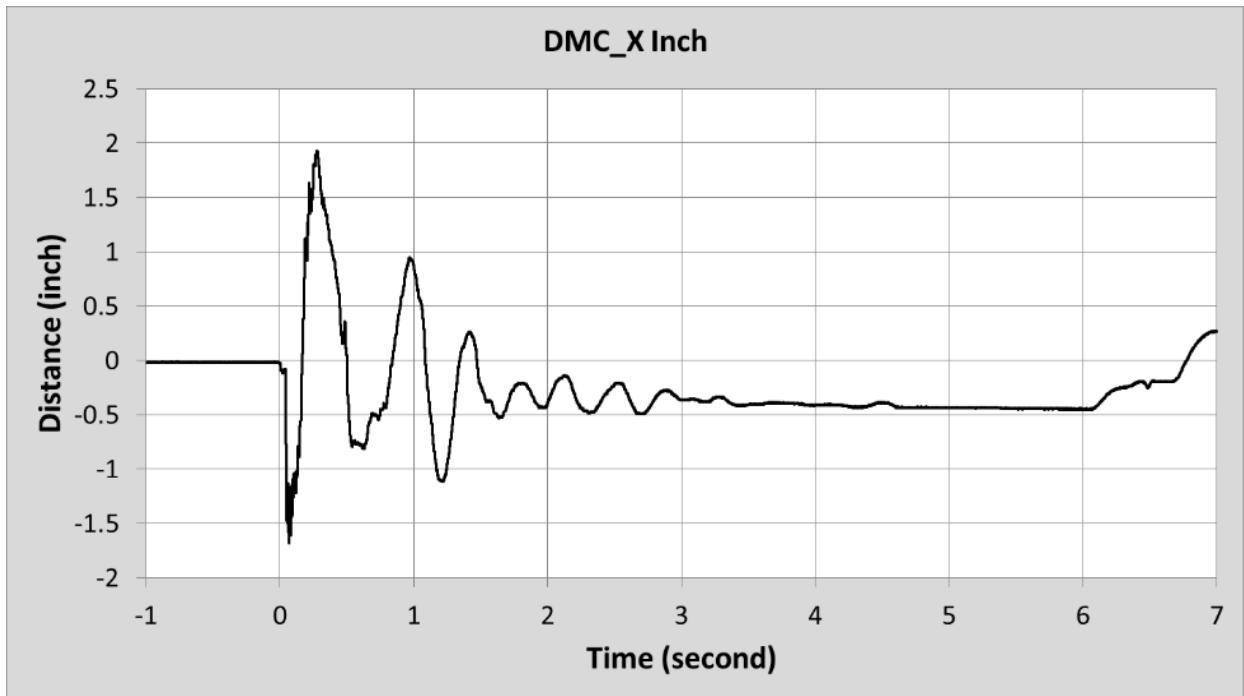


Figure E43. DMC_X String Potentiometer Data

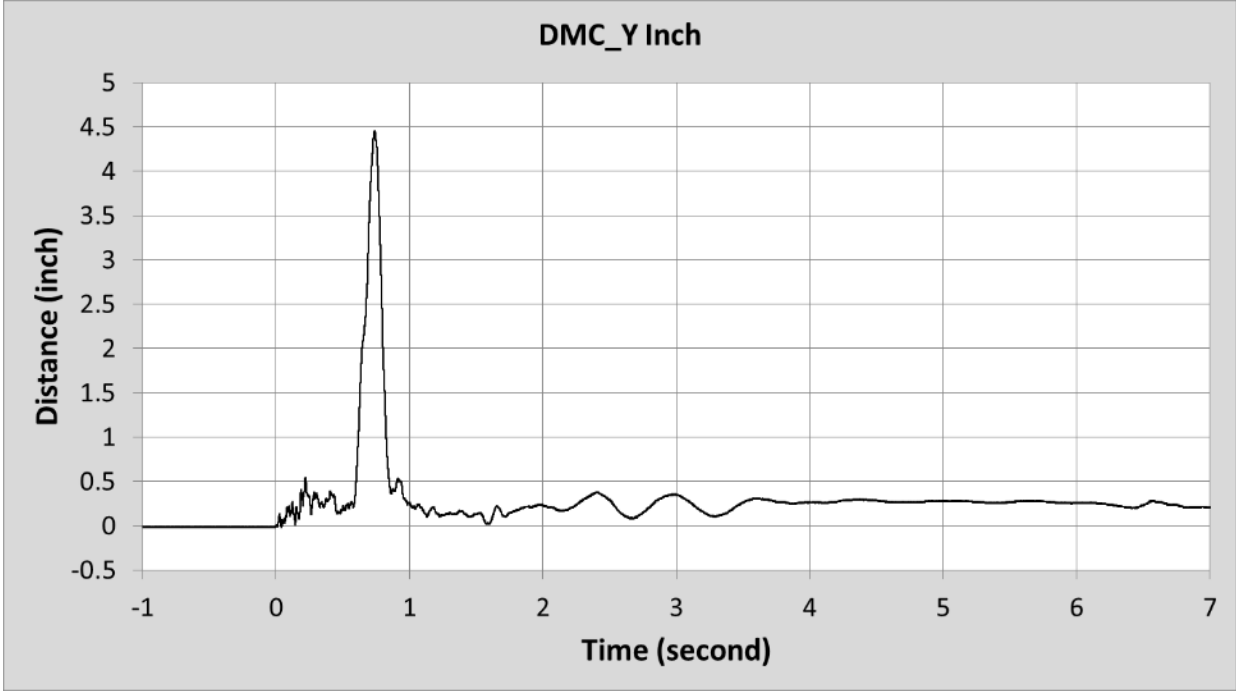


Figure E44. DMC_Y String Potentiometer Data

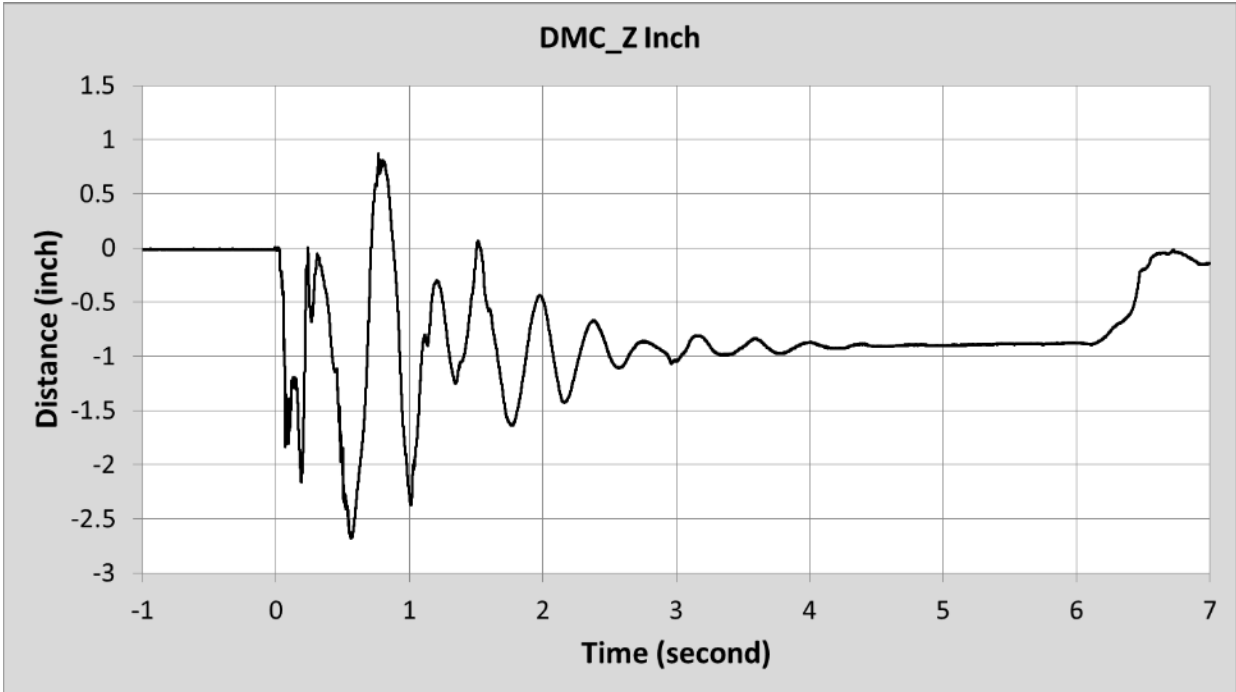


Figure E45. DMC_Z String Potentiometer Data

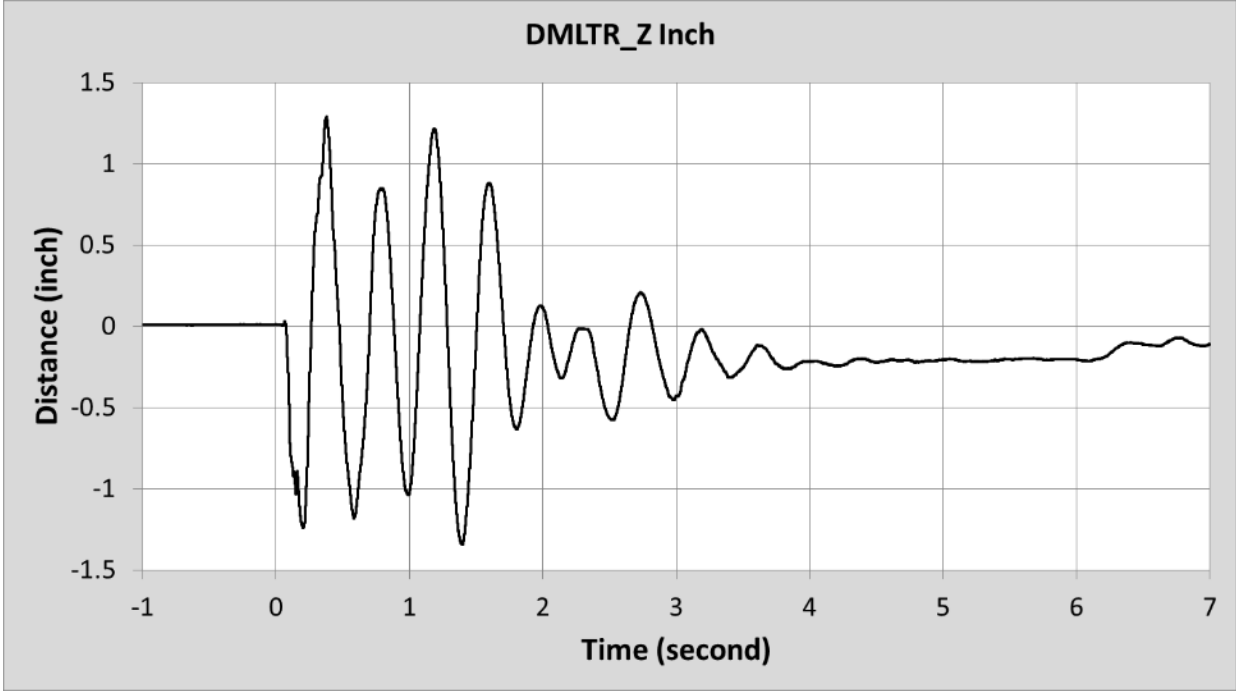


Figure E46. DMLTR_Z String Potentiometer Data

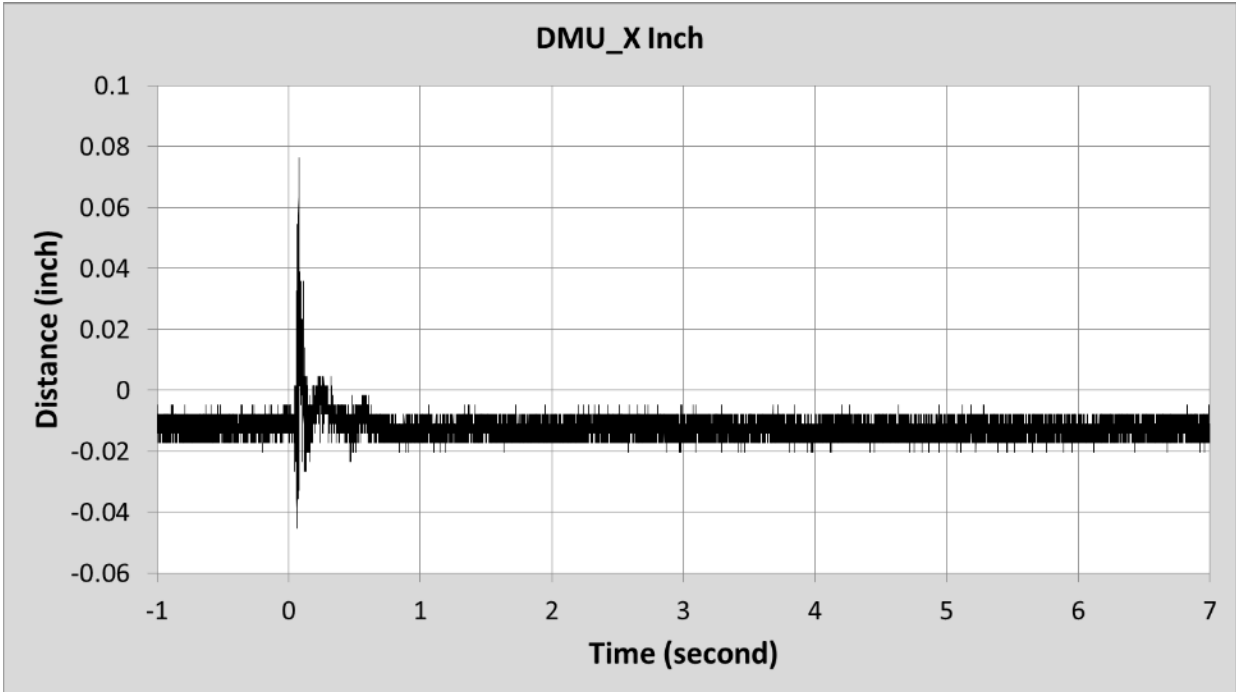


Figure E47. DMU_X String Potentiometer Data

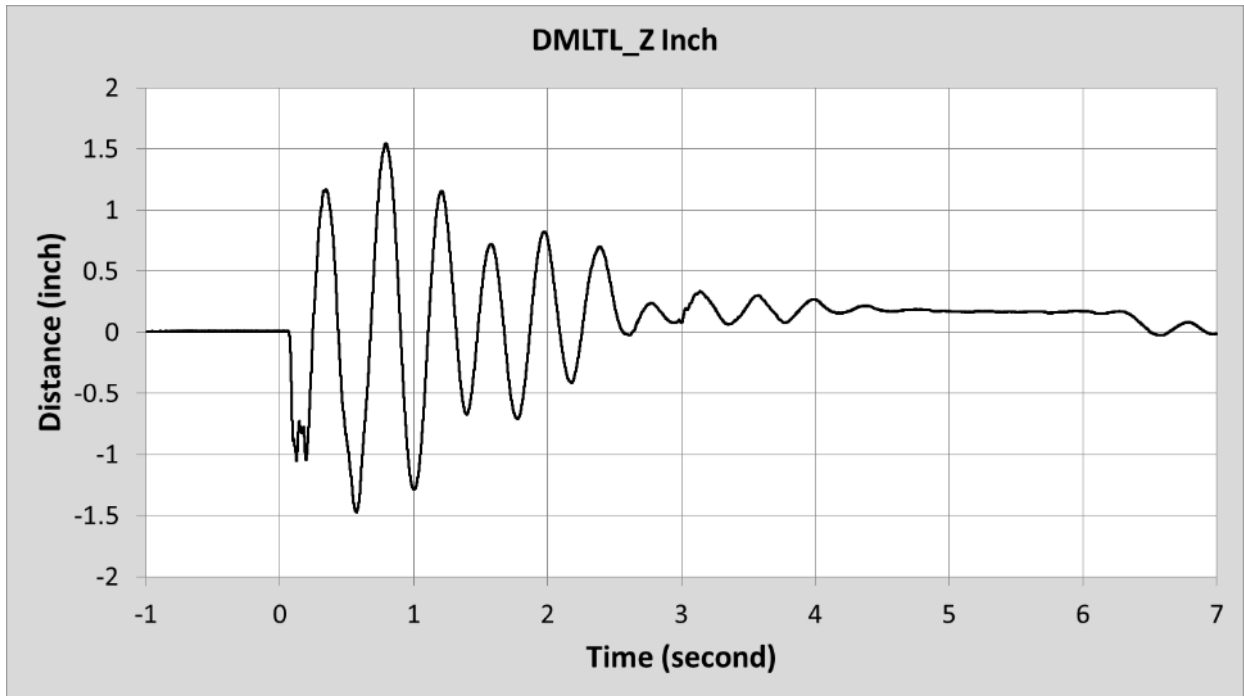


Figure E48. DMLTL_Z String Potentiometer Data

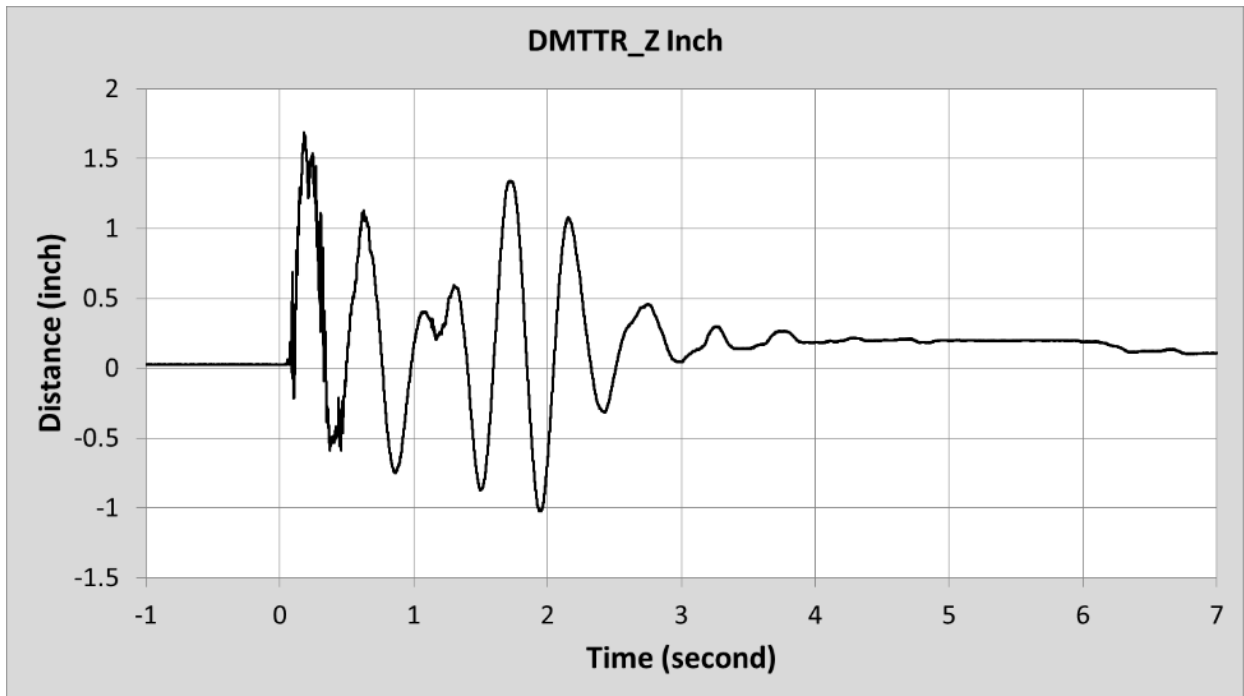


Figure E49. DMTTR_Z String Potentiometer Data

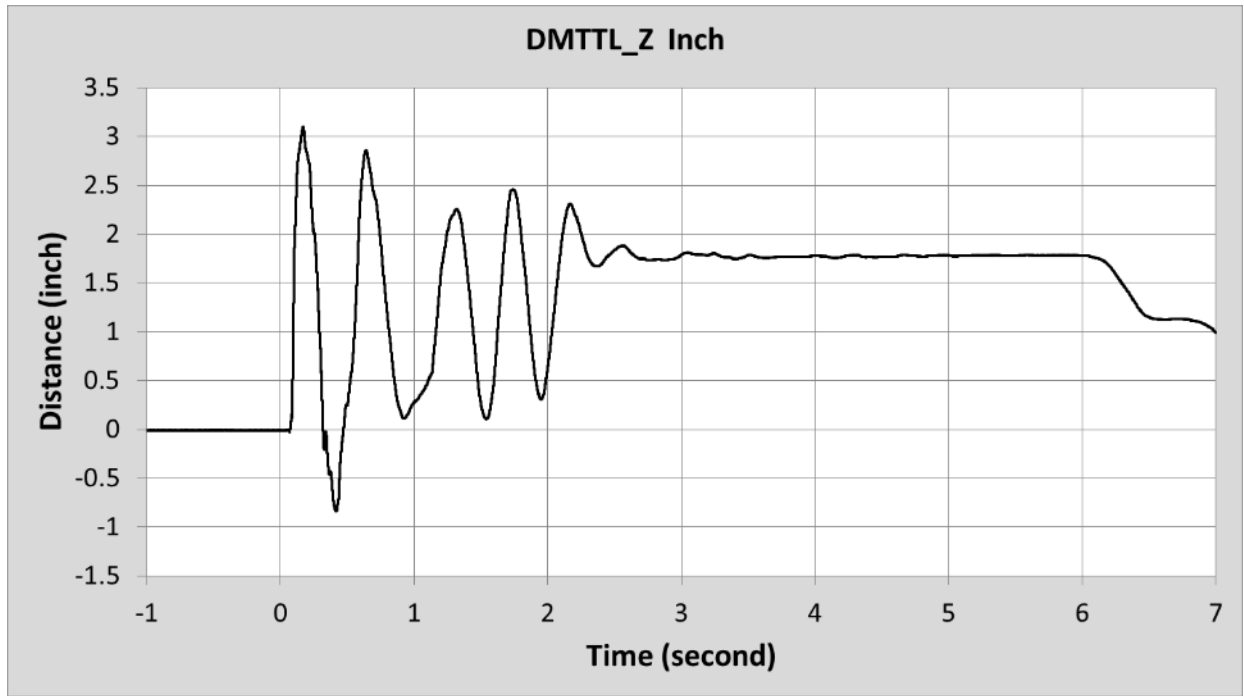


Figure E50. DMTTL_Z String Potentiometer Data

Appendix F. 10 mph Test Data

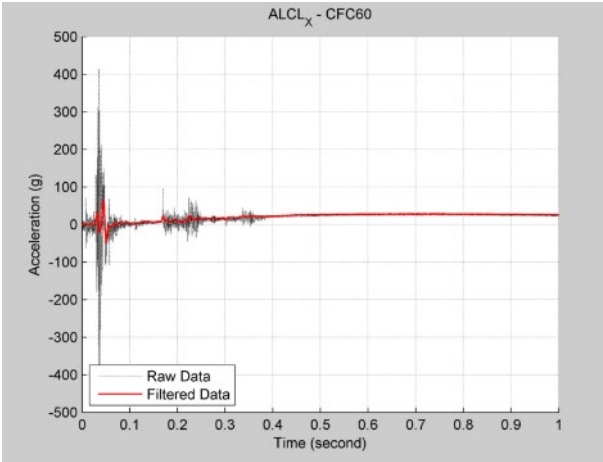


Figure F1. ALCL_X Accelerometer Data

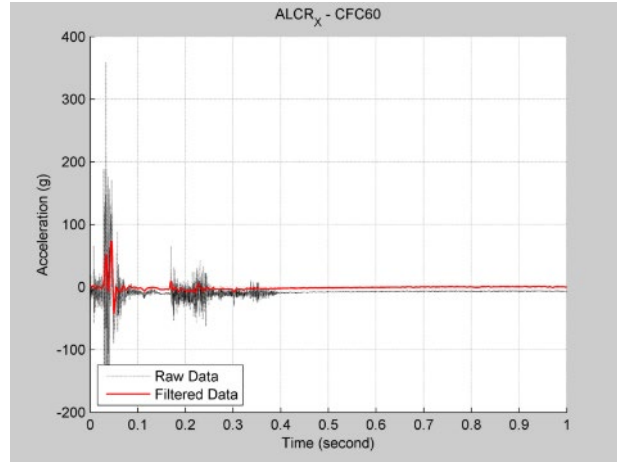


Figure F2. ALCR_X Accelerometer Data

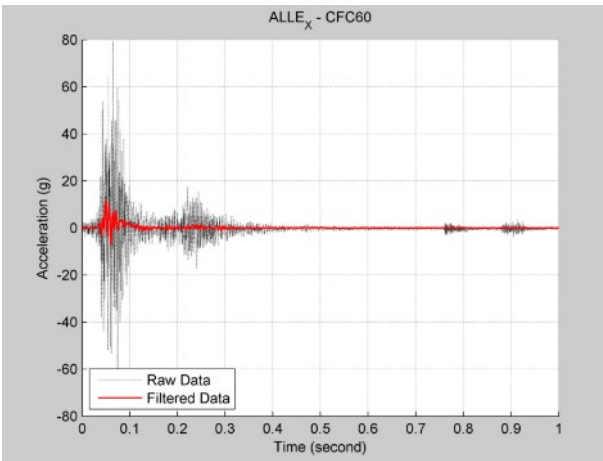


Figure F3. ALLE_X Accelerometer Data

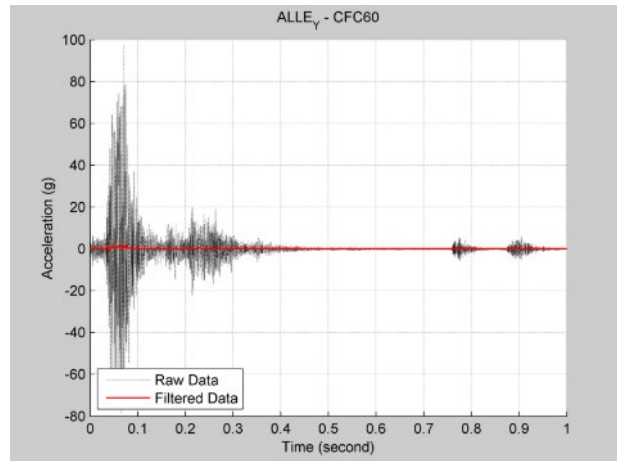


Figure F4. ALLE_Y Accelerometer Data

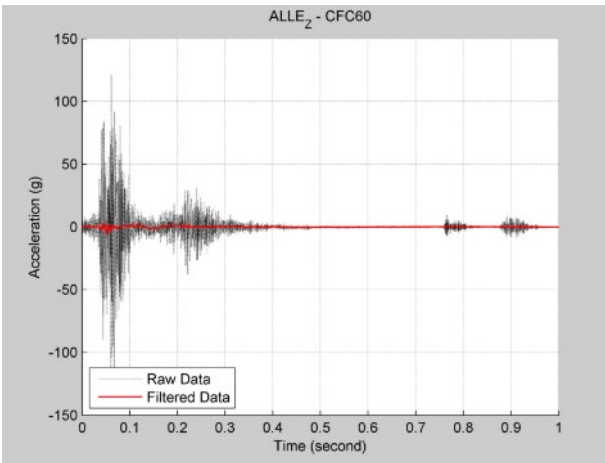


Figure F5. ALLE_Z Accelerometer Data

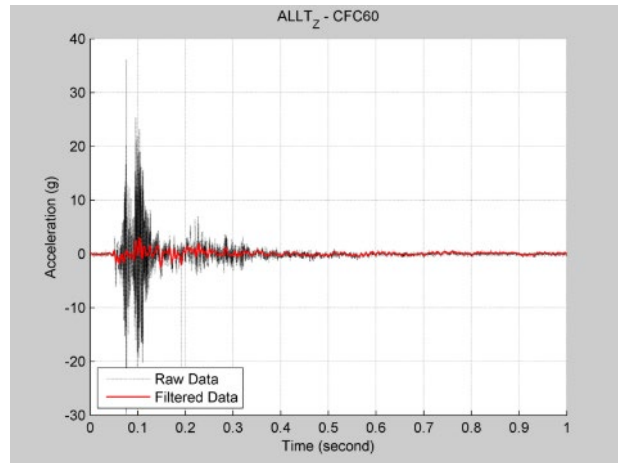


Figure F6. ALLT_Z Accelerometer Data

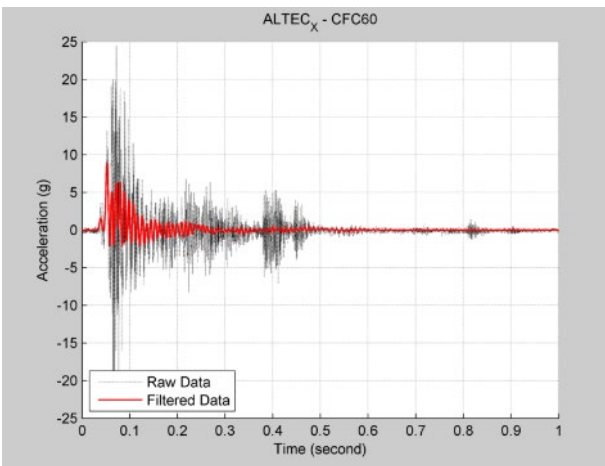


Figure F7. ALTEC_X Accelerometer Data

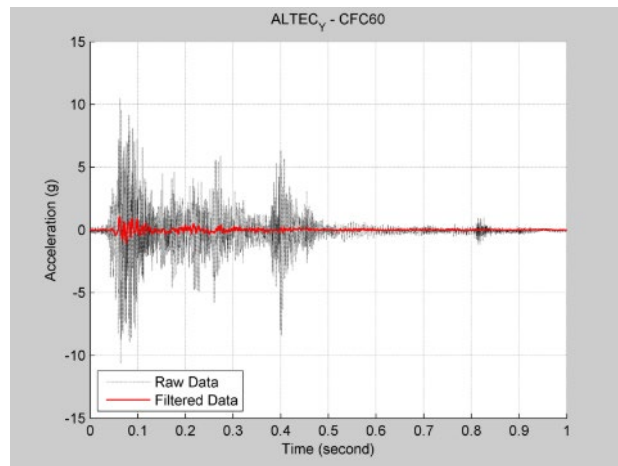


Figure F8. ALTEC_Y Accelerometer Data

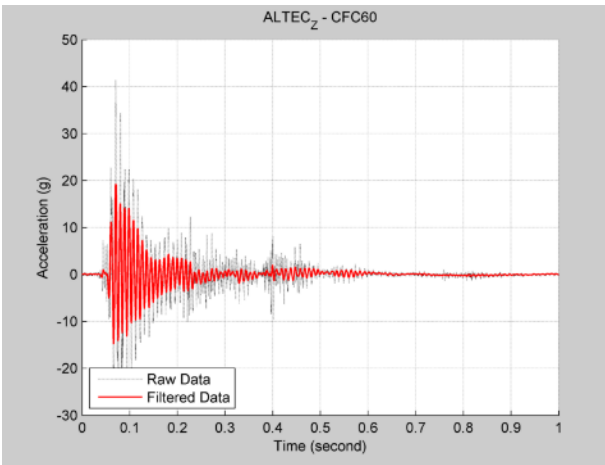


Figure F9. ALTEC_Z Accelerometer Data

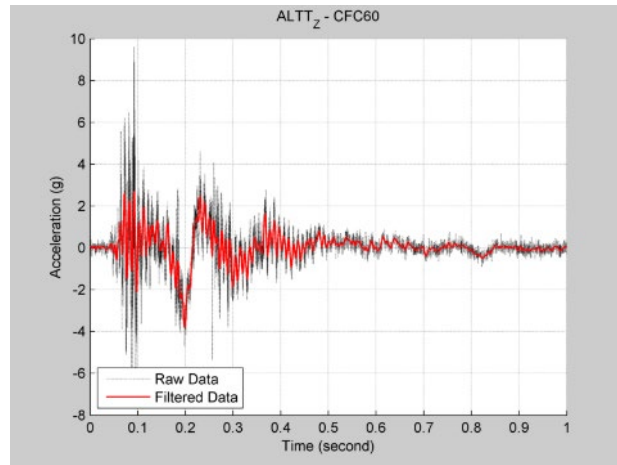


Figure F10. ALTT_Z Accelerometer Data

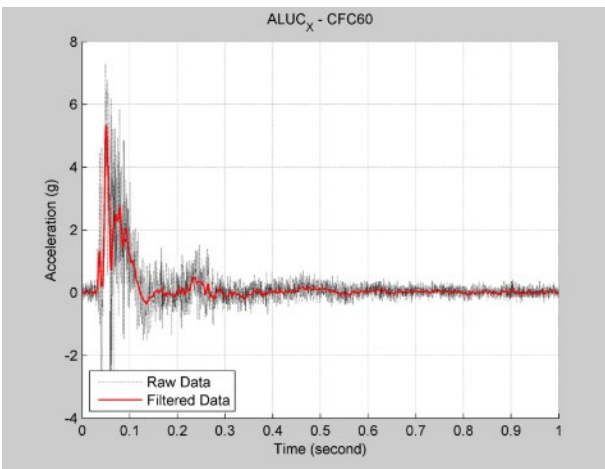


Figure F11. ALUC_X Accelerometer Data

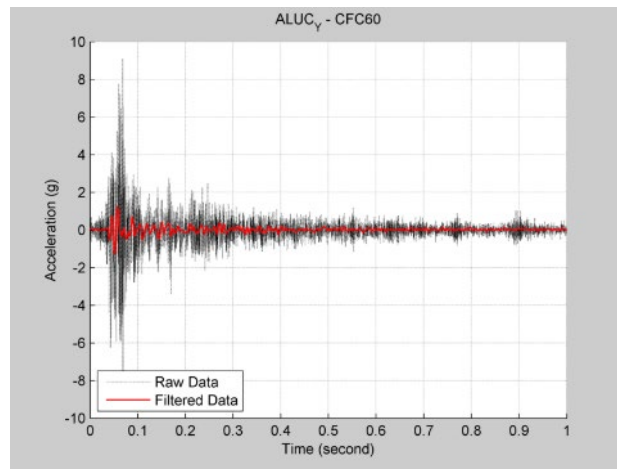


Figure F12. ALUC_Y Accelerometer Data

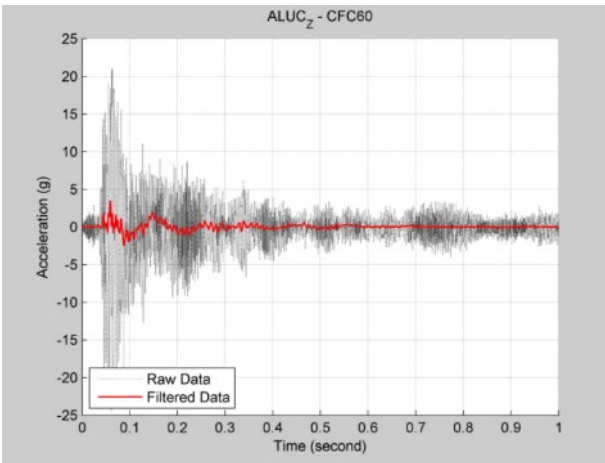


Figure F13. ALUC_Z Accelerometer Data

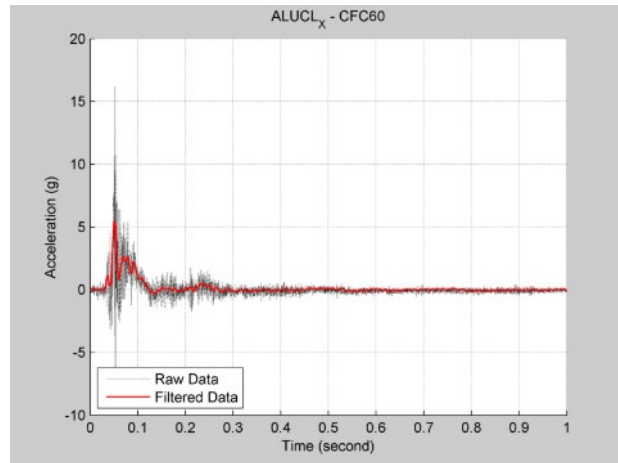


Figure F14. ALUCL_X Accelerometer Data

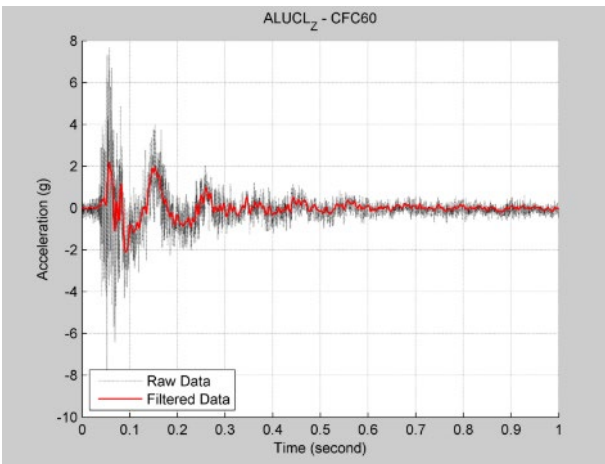


Figure F15. ALUCL_Z Accelerometer Data

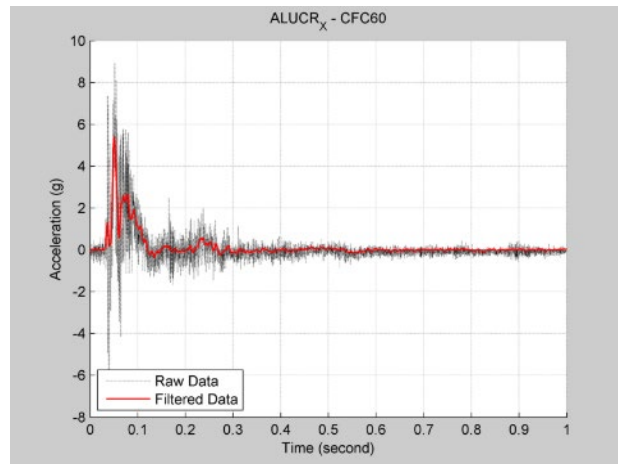


Figure F16. ALUCR_X Accelerometer Data

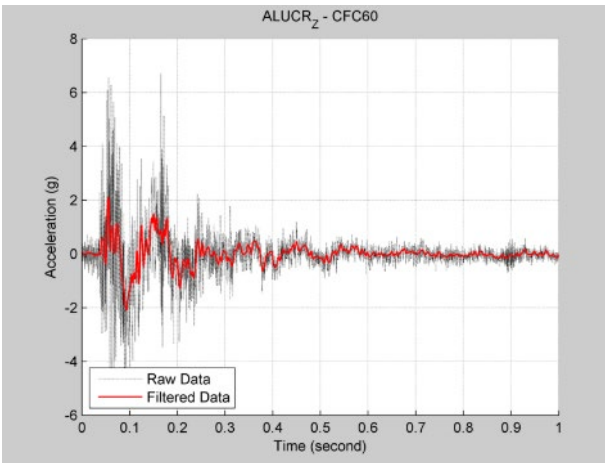


Figure F17. ALUCR_Z Accelerometer Data

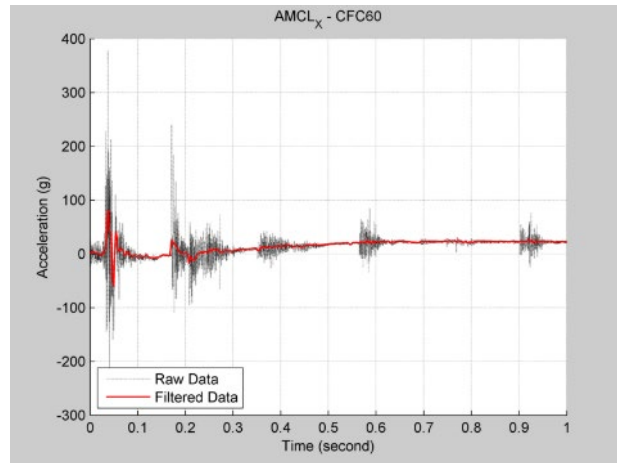


Figure F18. AMCL_X Accelerometer Data

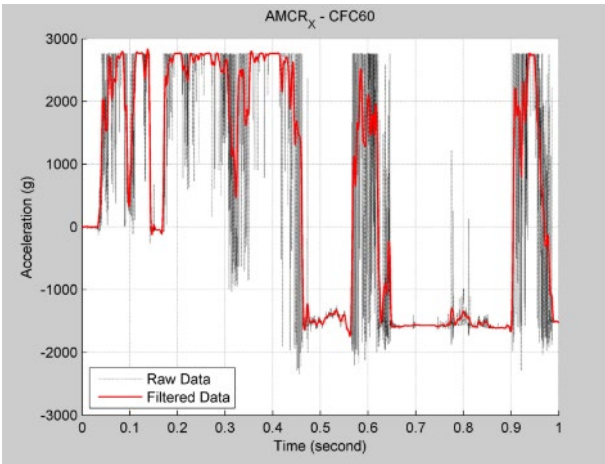


Figure F19. AMCR_X Accelerometer Data

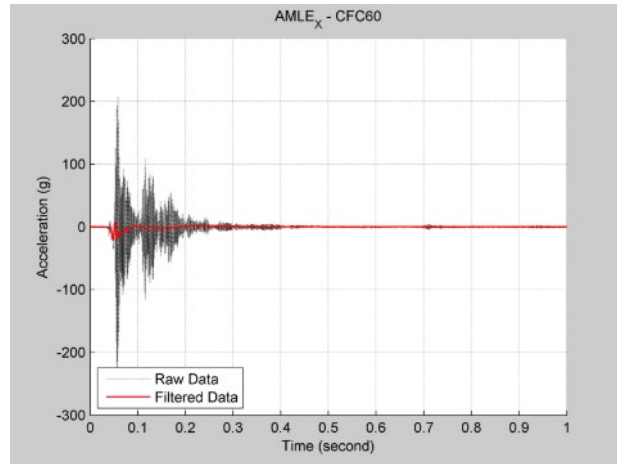


Figure F20. AMLE_X Accelerometer Data

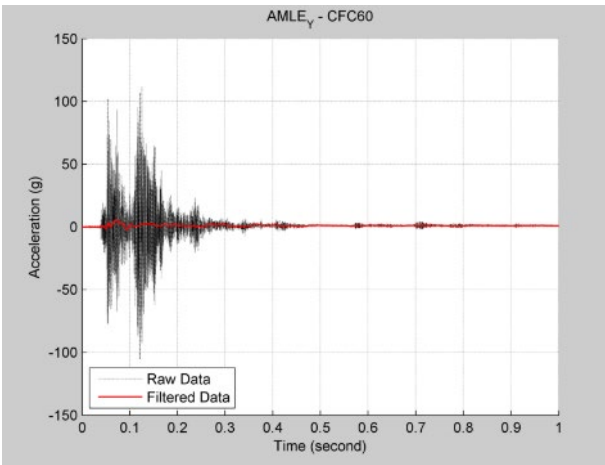


Figure F21. AMLE_Y Accelerometer Data

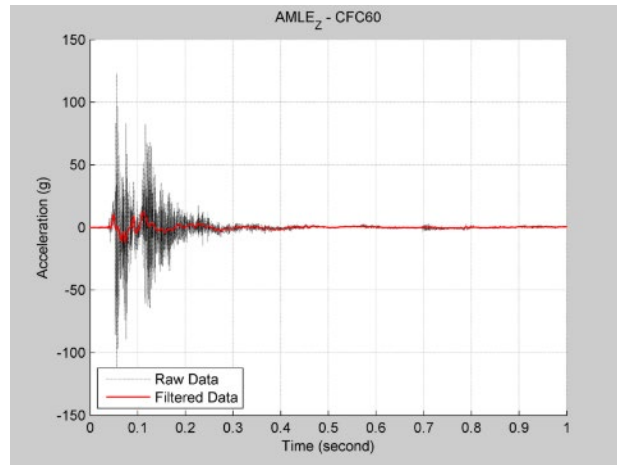


Figure F22. AMLE_Z Accelerometer Data

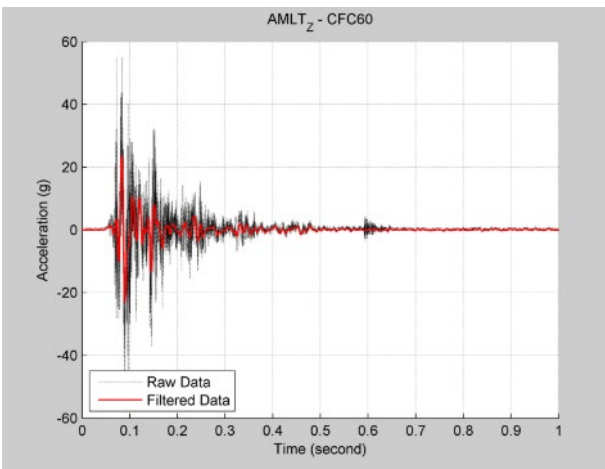


Figure F23. AMLT_Z Accelerometer Data

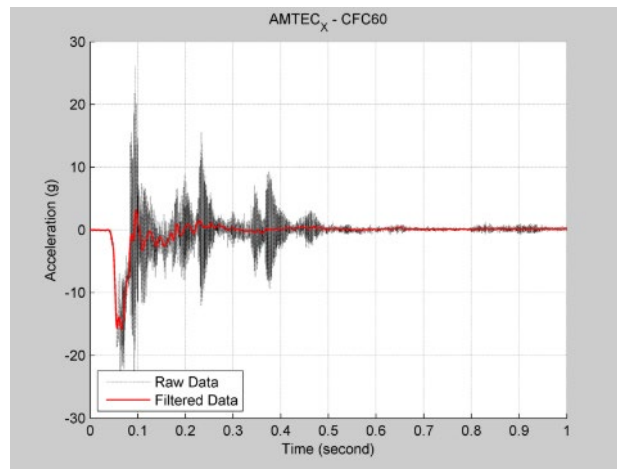


Figure F24. AMTEC_X Accelerometer Data

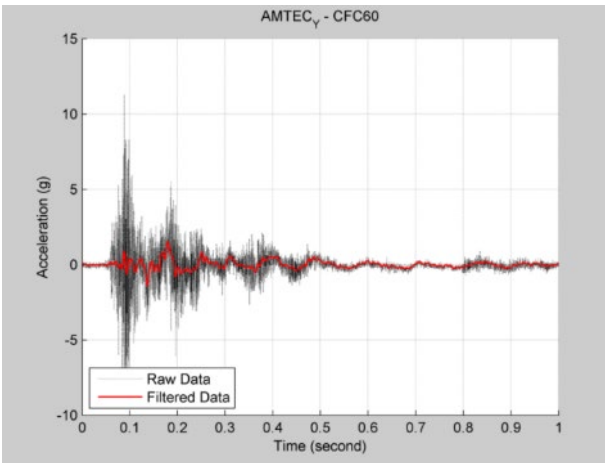


Figure F25. AMTEC_Y Accelerometer Data

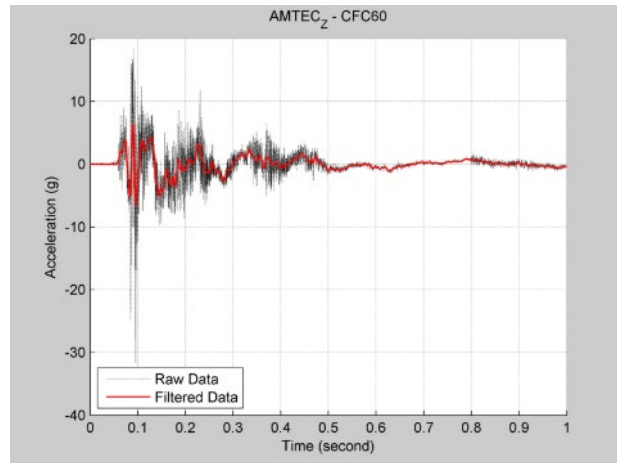


Figure F26. AMTEC_Z Accelerometer Data

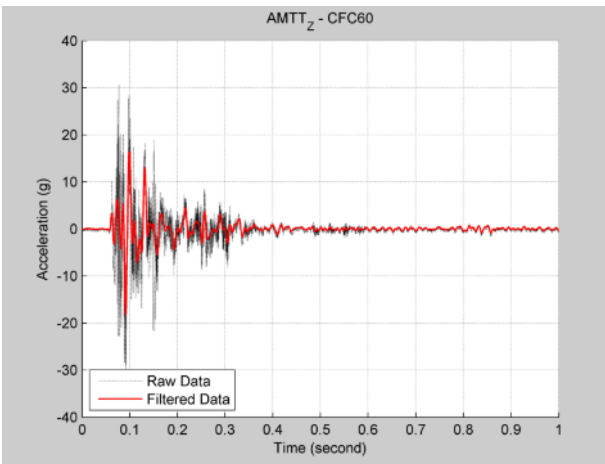


Figure F27. AMTT_Z Accelerometer Data

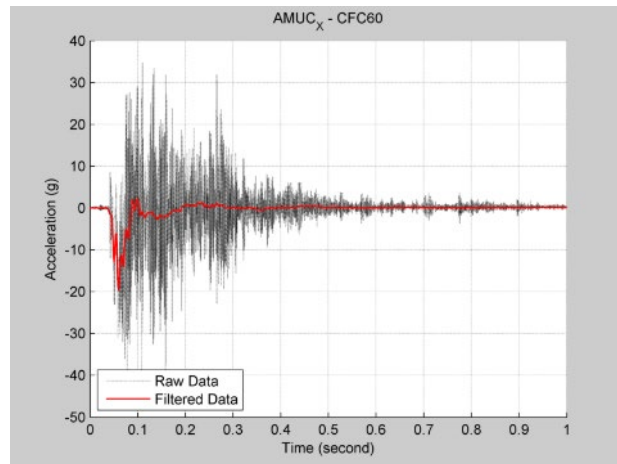


Figure F28. AMUC_X Accelerometer Data

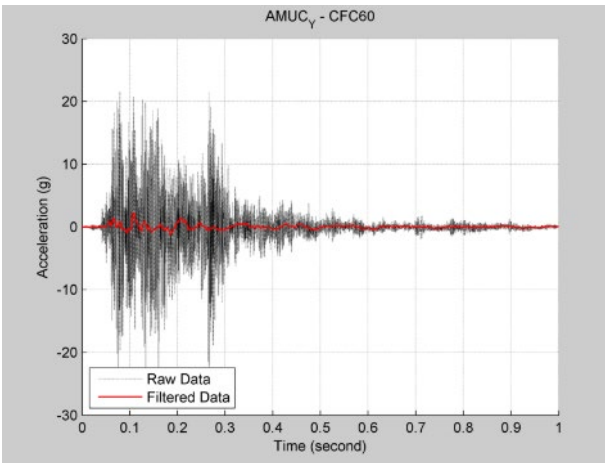


Figure F29. AMUC_Y Accelerometer Data

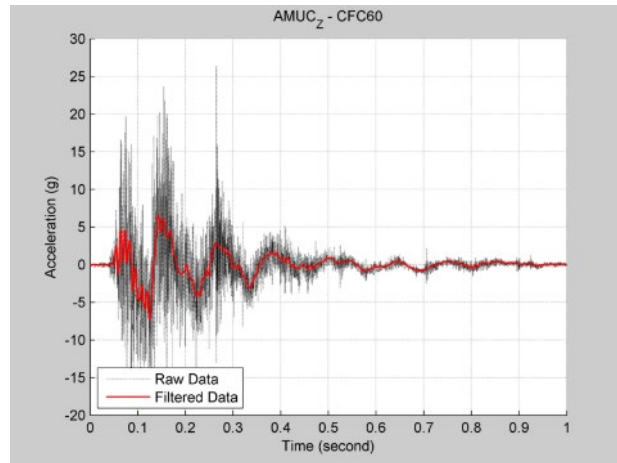


Figure F30. AMUC_Z Accelerometer Data

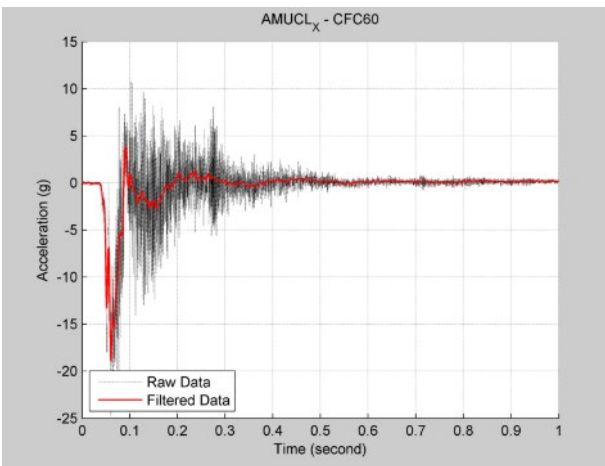


Figure F31. AMUCL_X Accelerometer Data

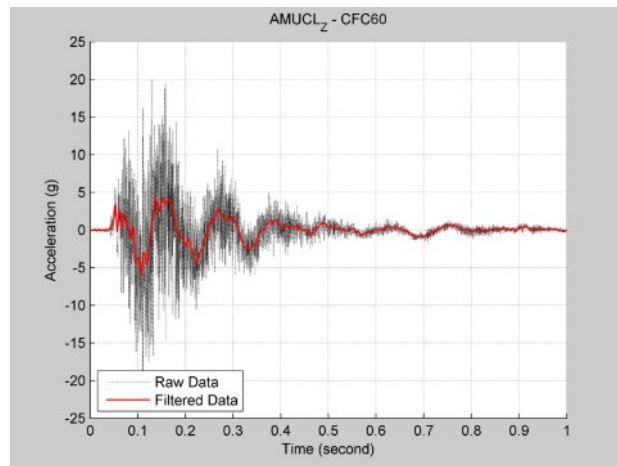


Figure F32. AMUCL_Z Accelerometer Data

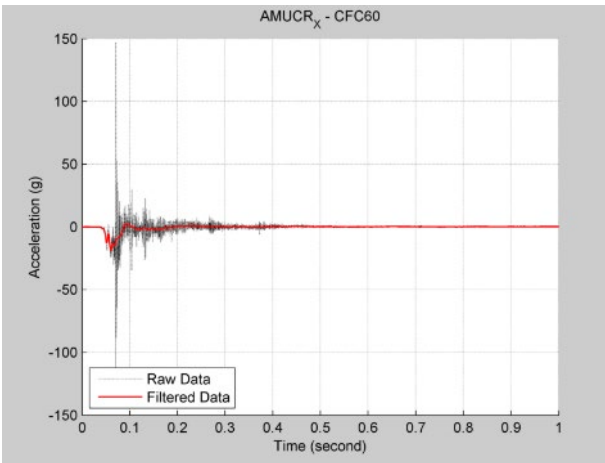


Figure F33. AMUCR_X Accelerometer Data

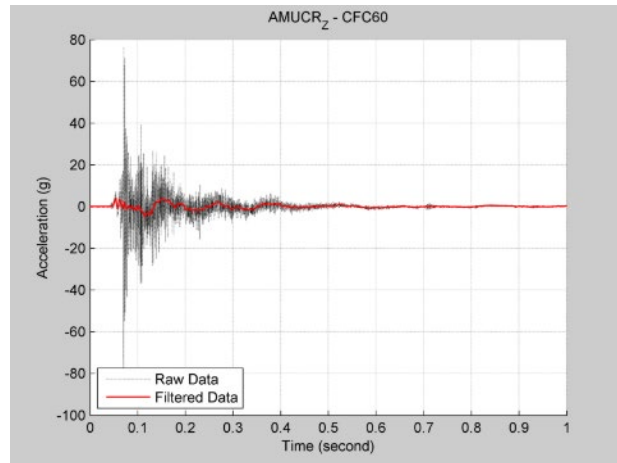


Figure F34. AMUCR_Z Accelerometer Data

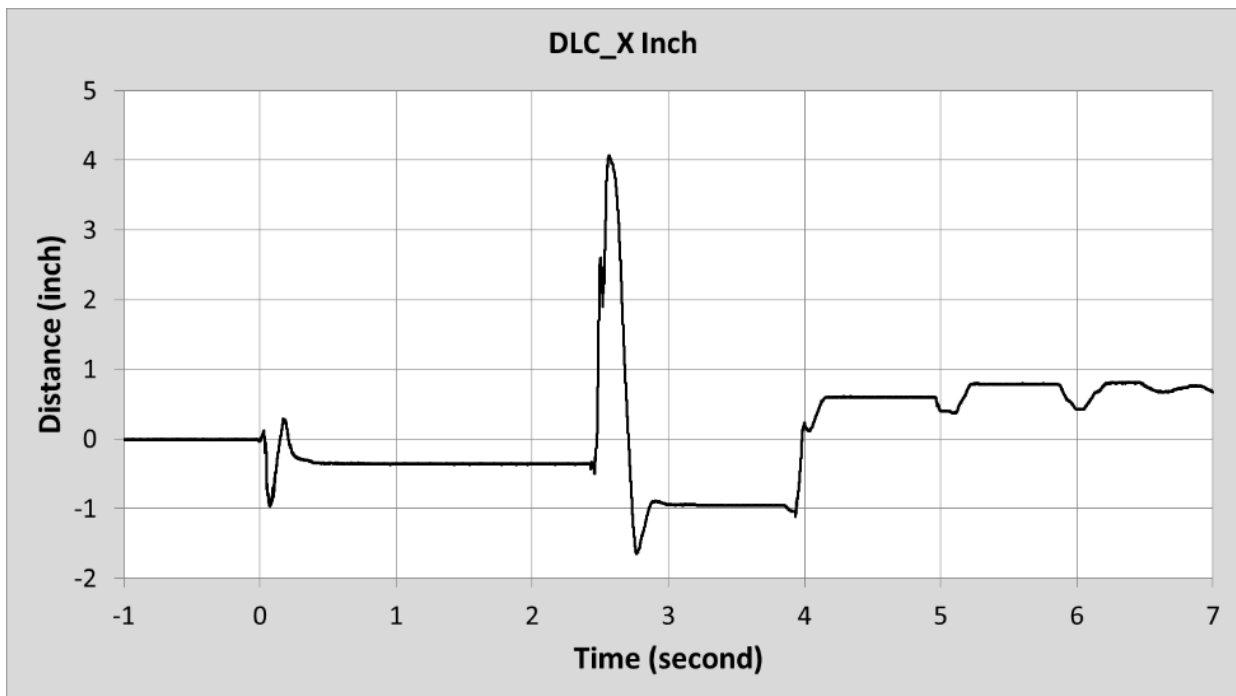


Figure F35. DLC_X String Potentiometer Data

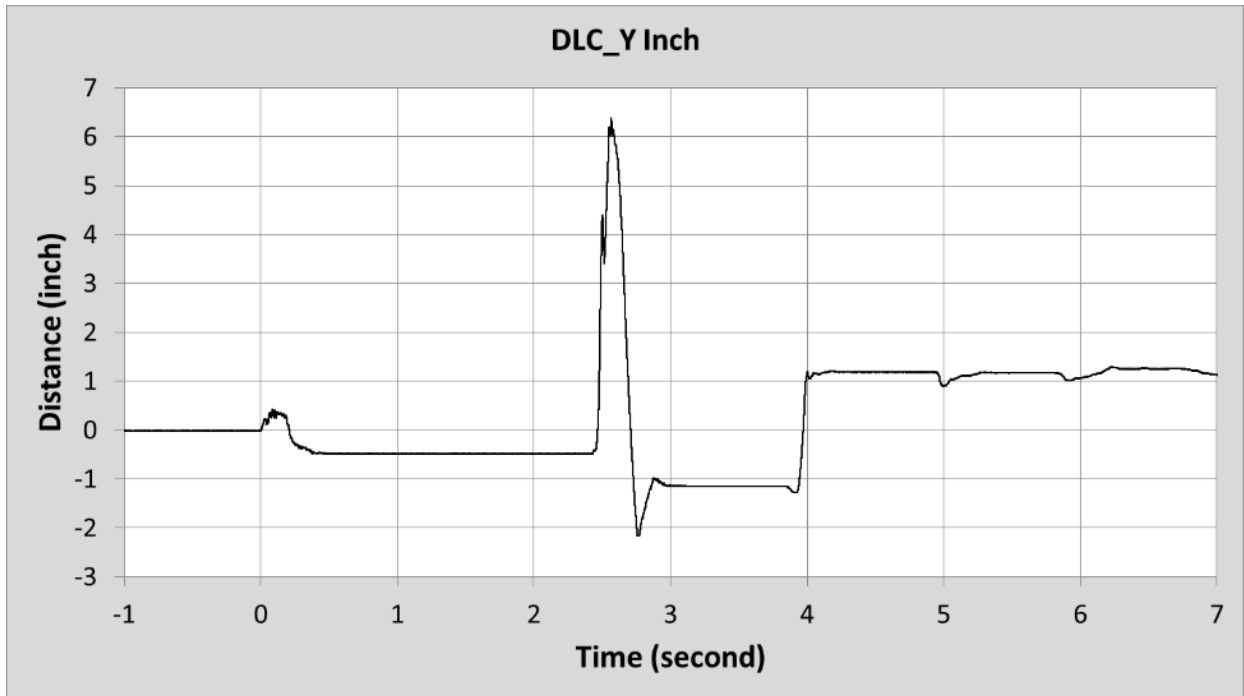


Figure F36. DLC_Y String Potentiometer Data

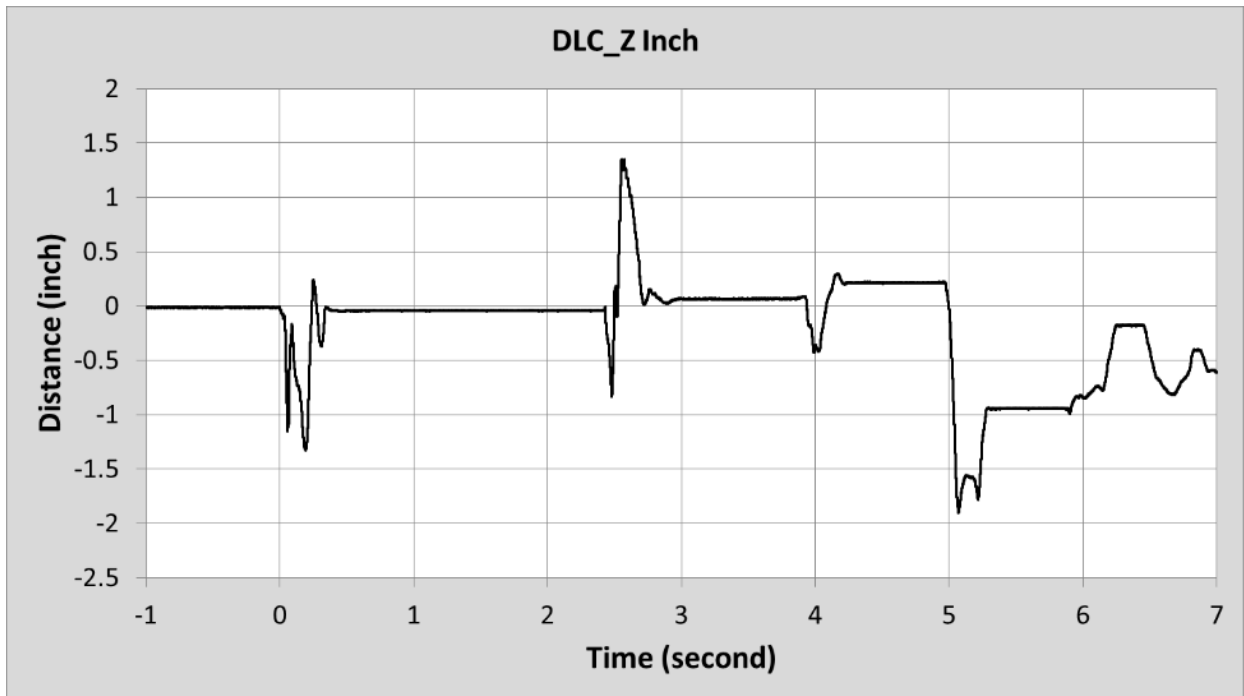


Figure F37. DLC_Z String Potentiometer Data

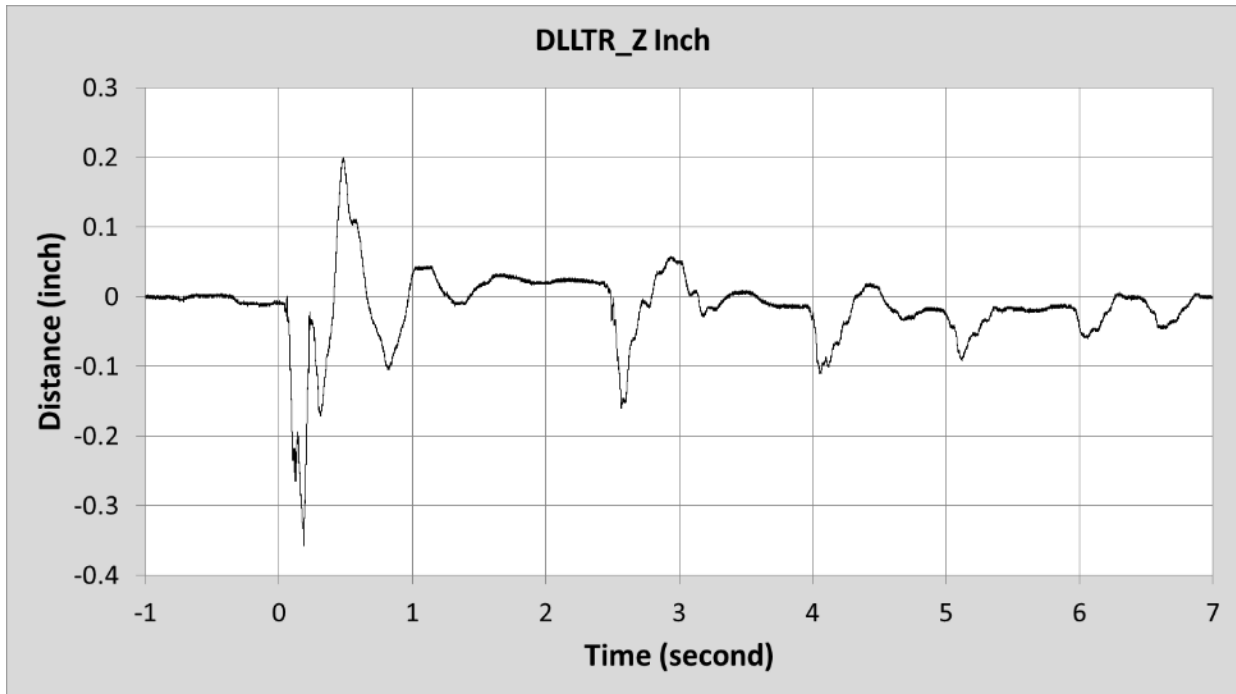


Figure F38. DLLTR_Z String Potentiometer Data

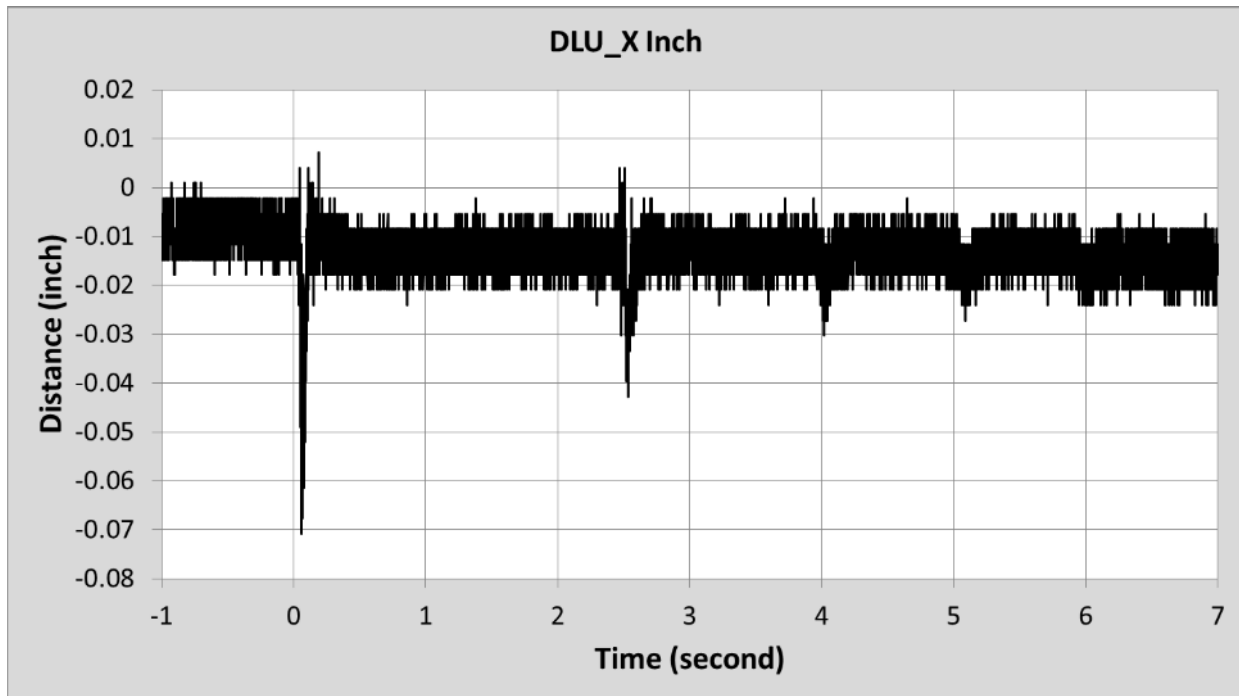


Figure F39. DLU_X String Potentiometer Data

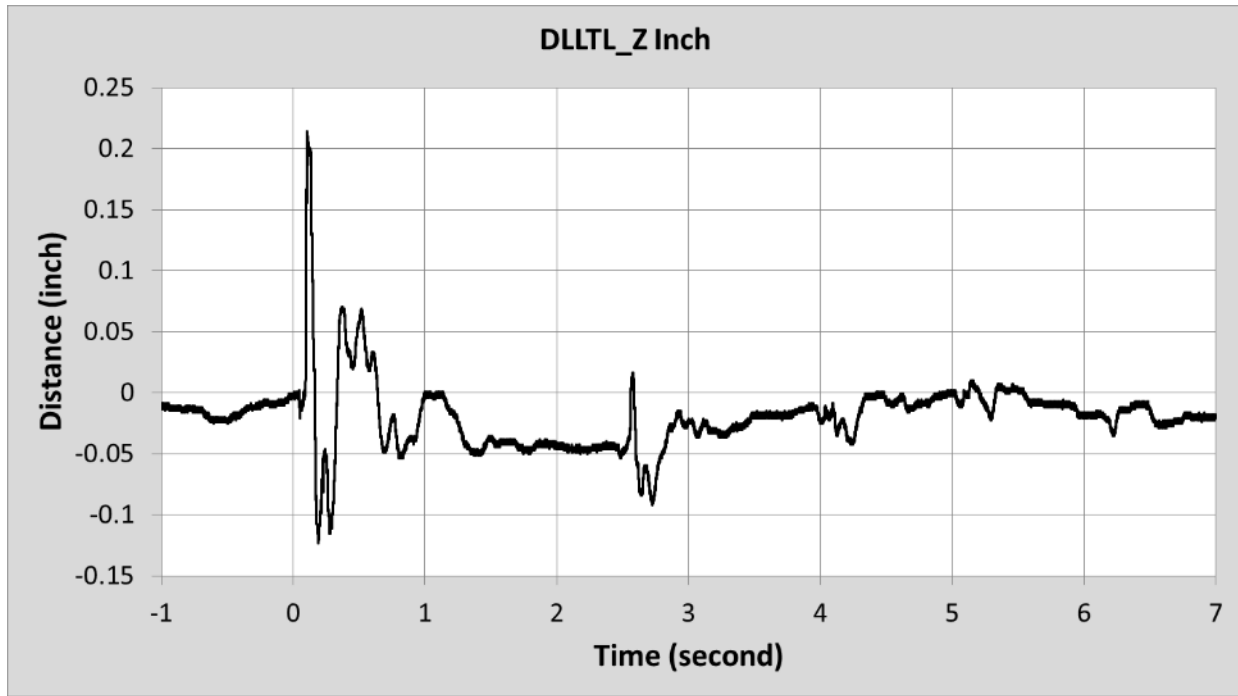


Figure F40. DLLTL_Z String Potentiometer Data

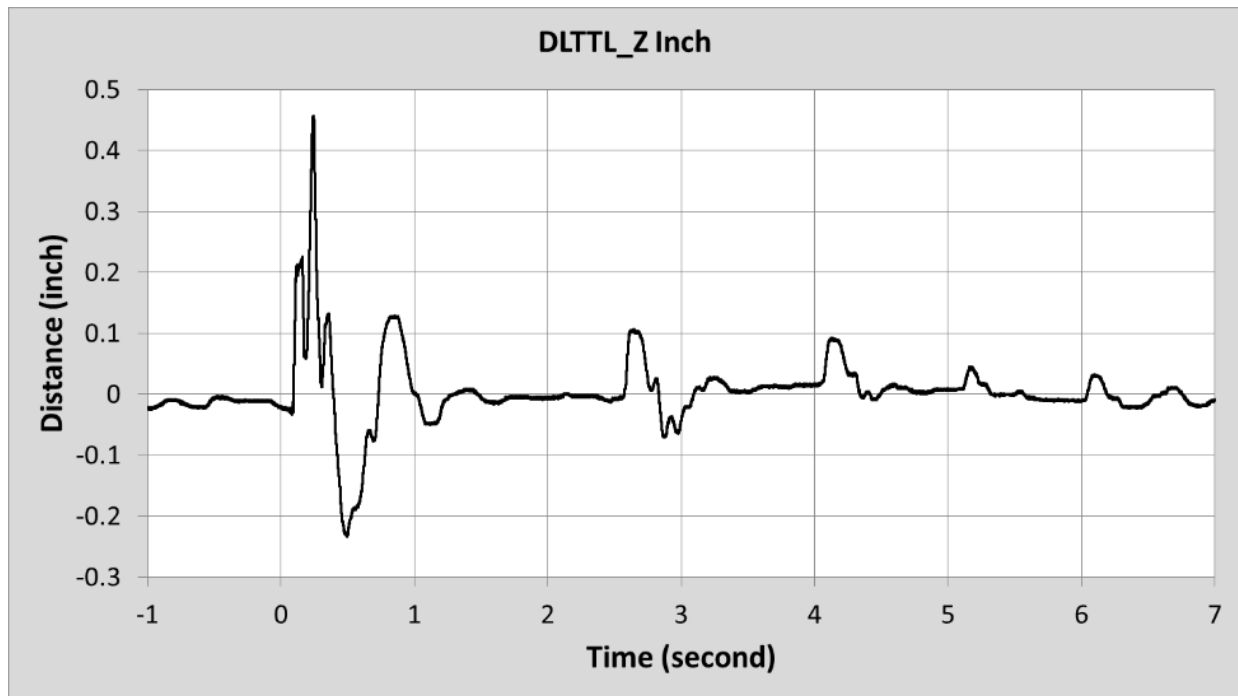


Figure F41. DLTTL_Z String Potentiometer Data

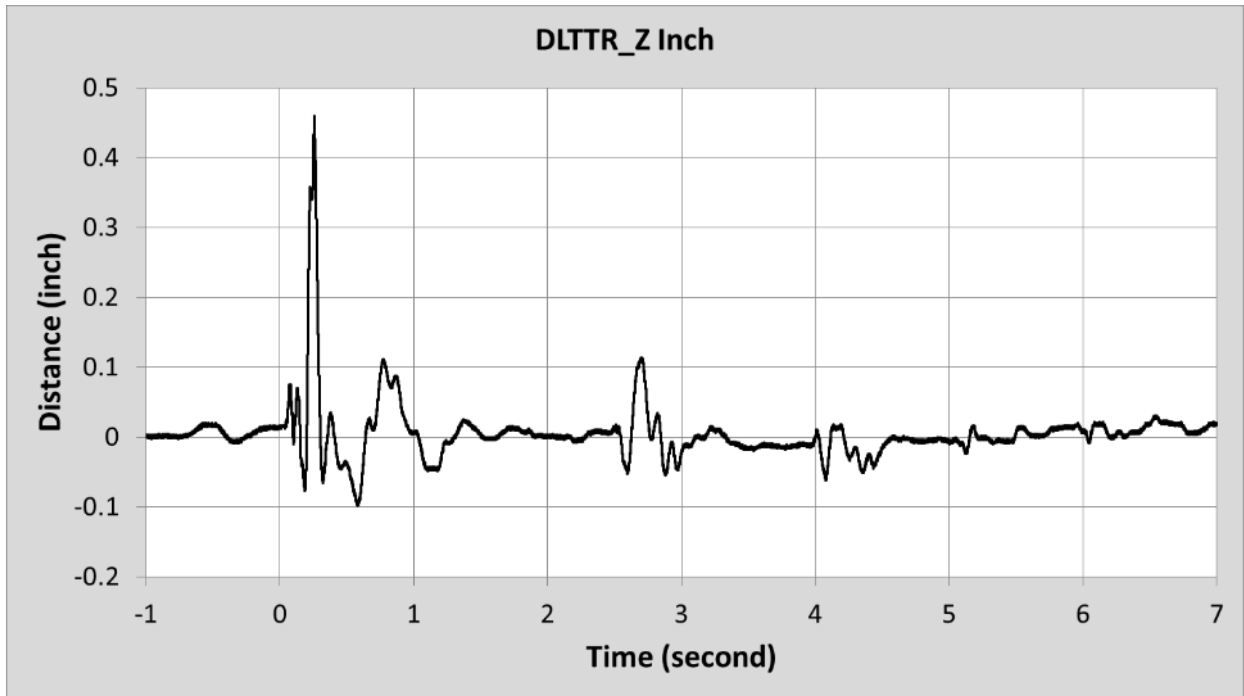


Figure F42. DLTTR_Z String Potentiometer Data

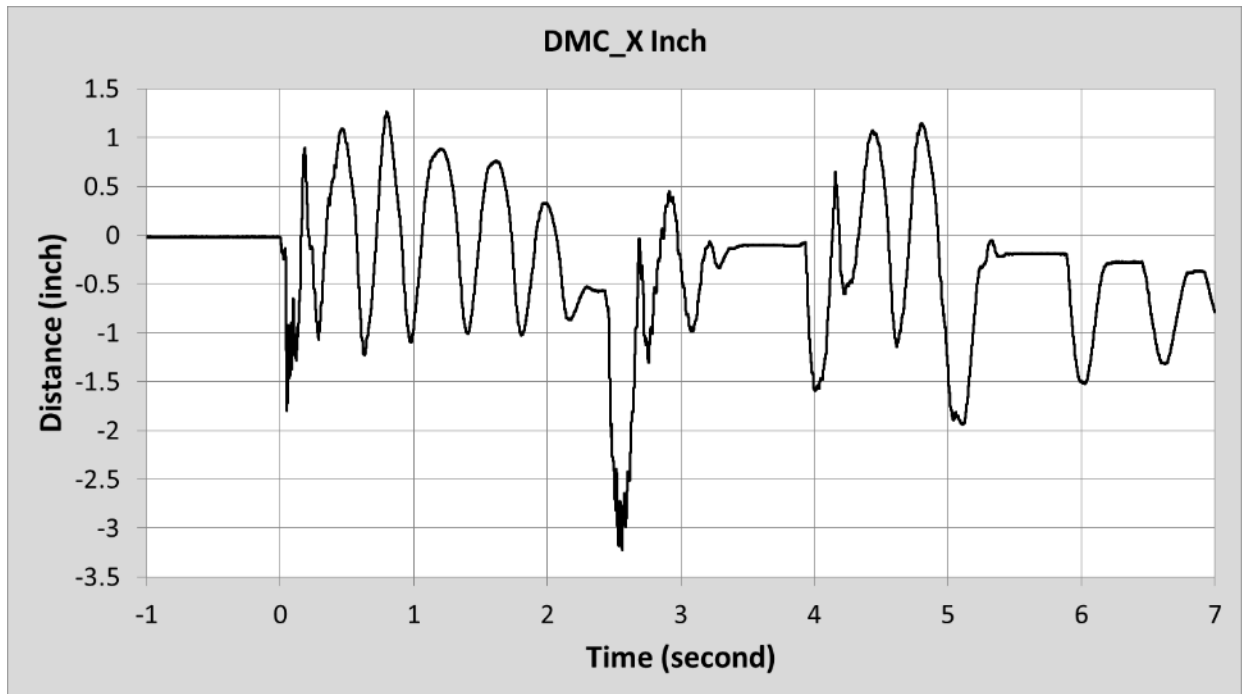


Figure F43. DMC_X String Potentiometer Data

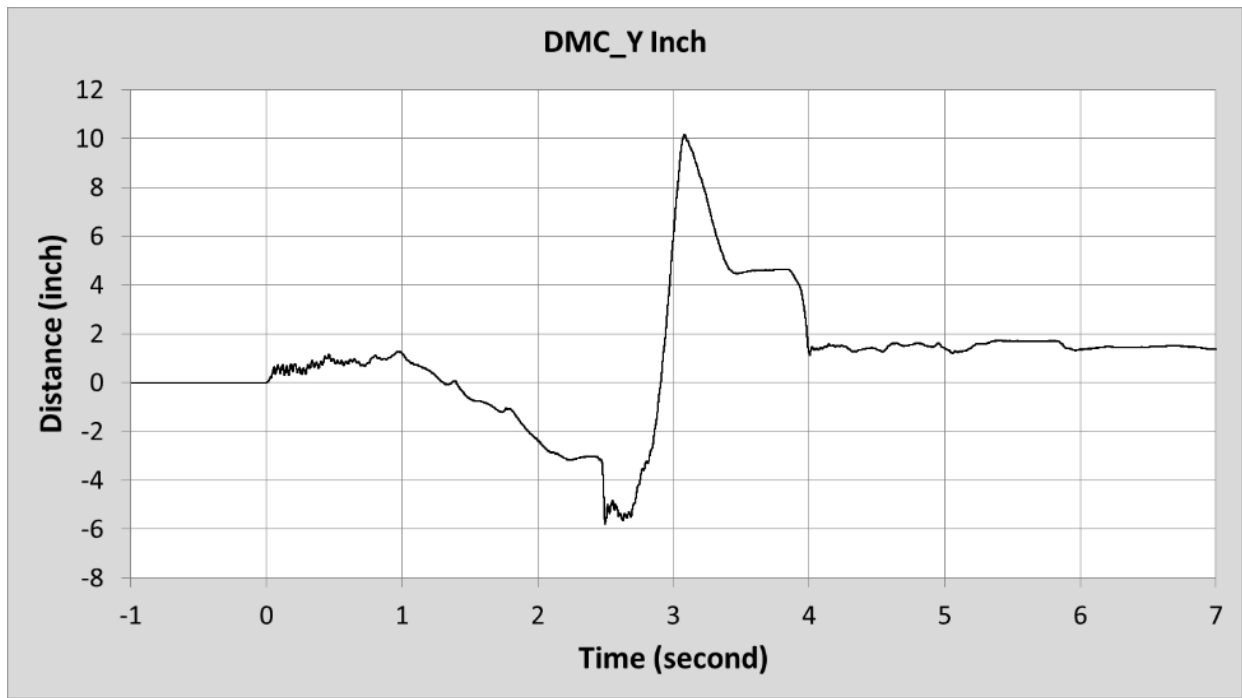


Figure F44. DMC_Y String Potentiometer Data

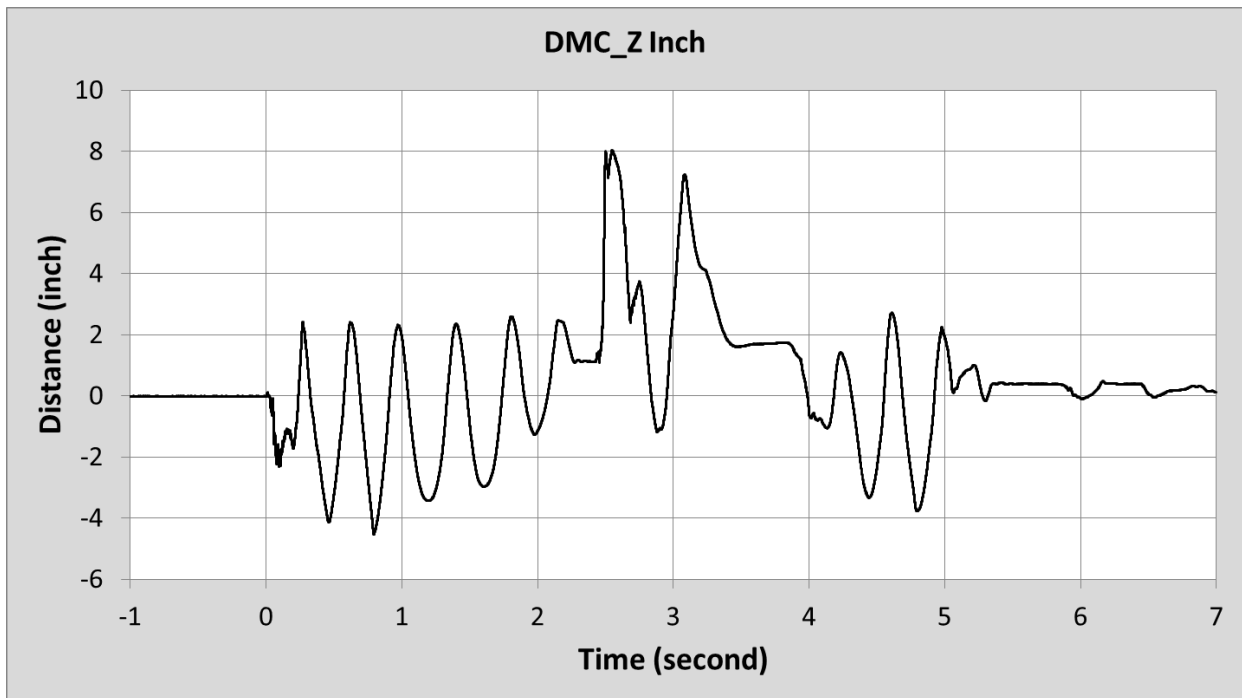


Figure F45. DMC_Z String Potentiometer Data

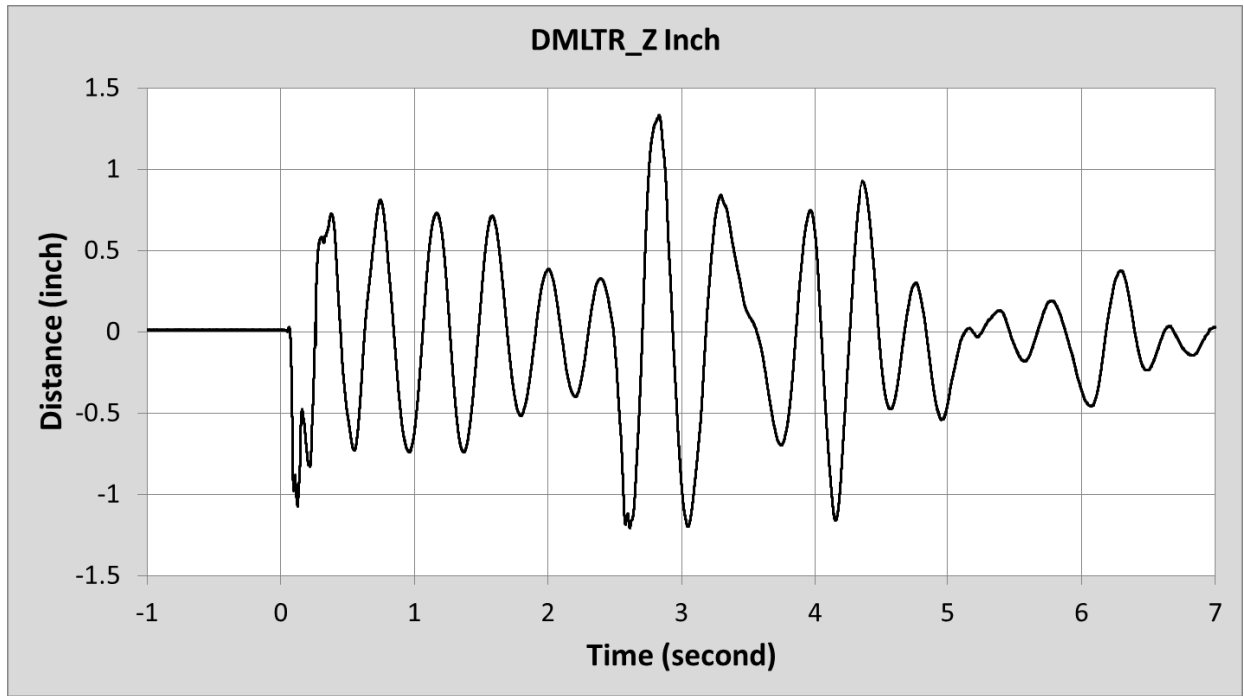


Figure F46. DMLTR_Z String Potentiometer Data

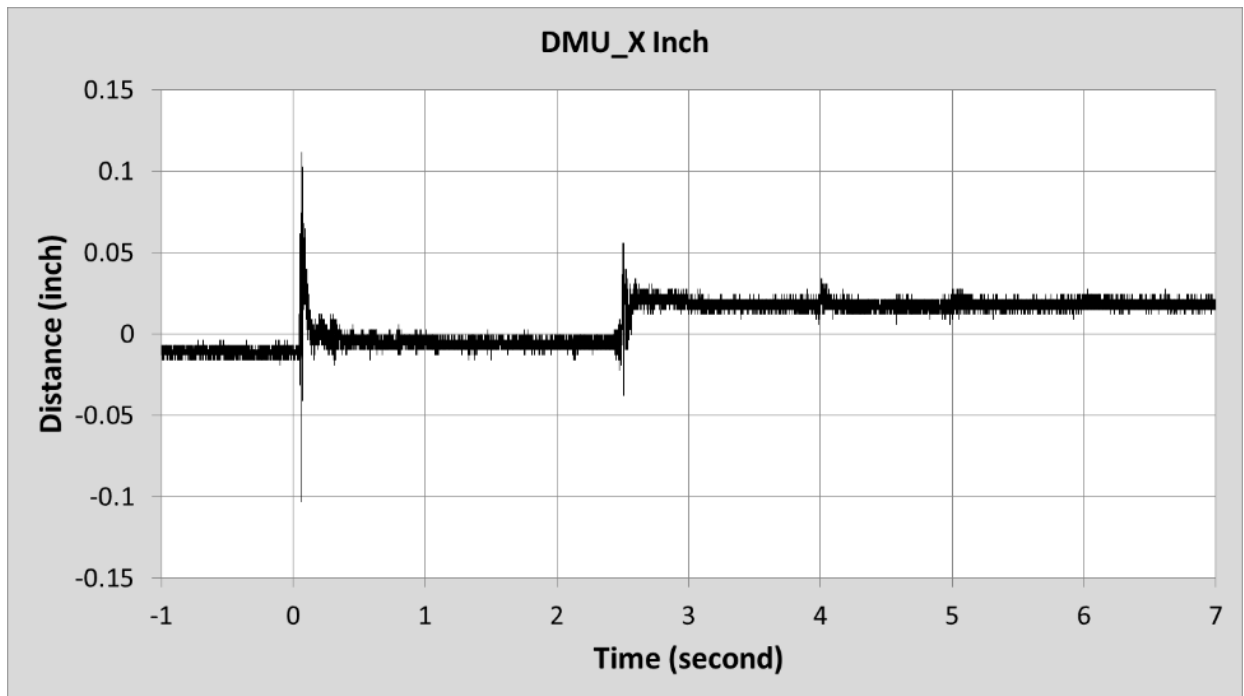


Figure F47. DMU_X String Potentiometer Data

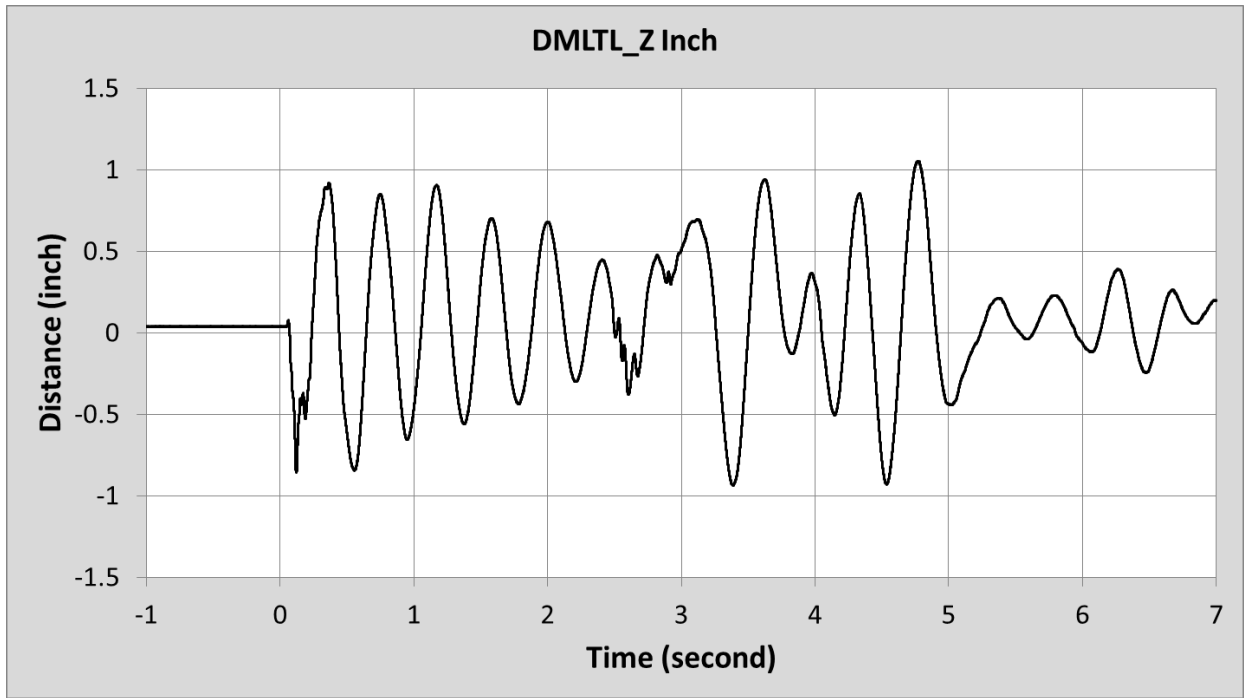


Figure F48. DMLTL_Z String Potentiometer Data

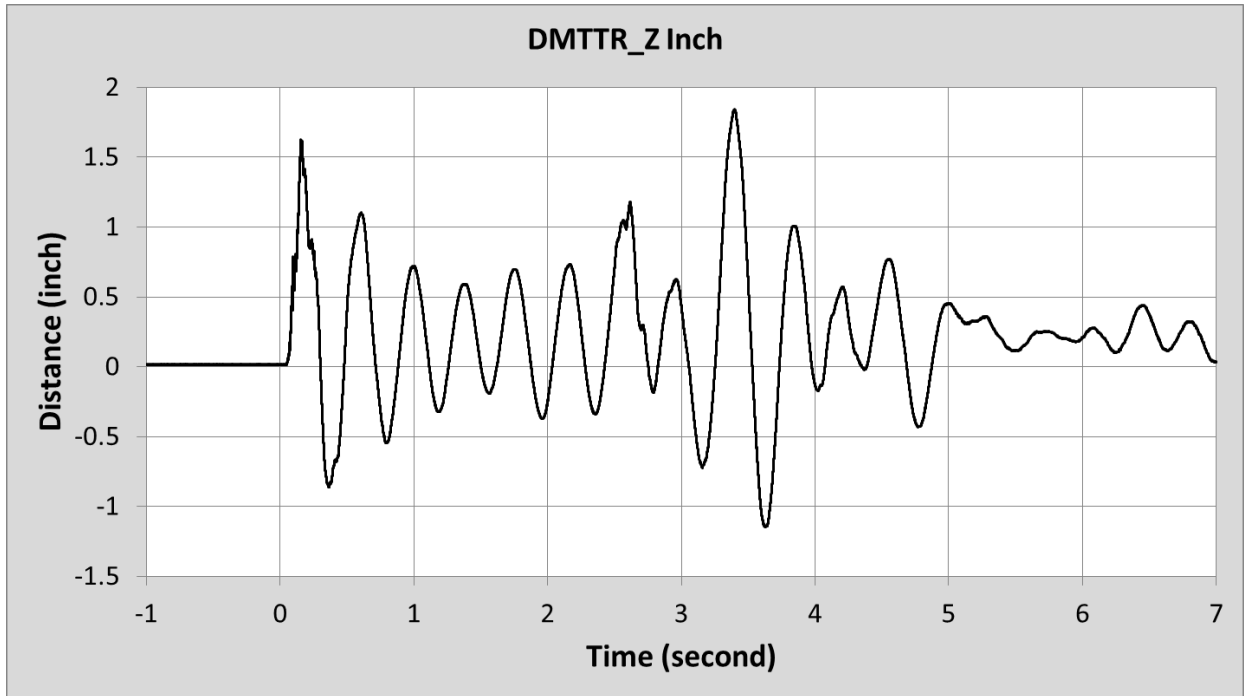


Figure F49. DMTTR_Z String Potentiometer Data

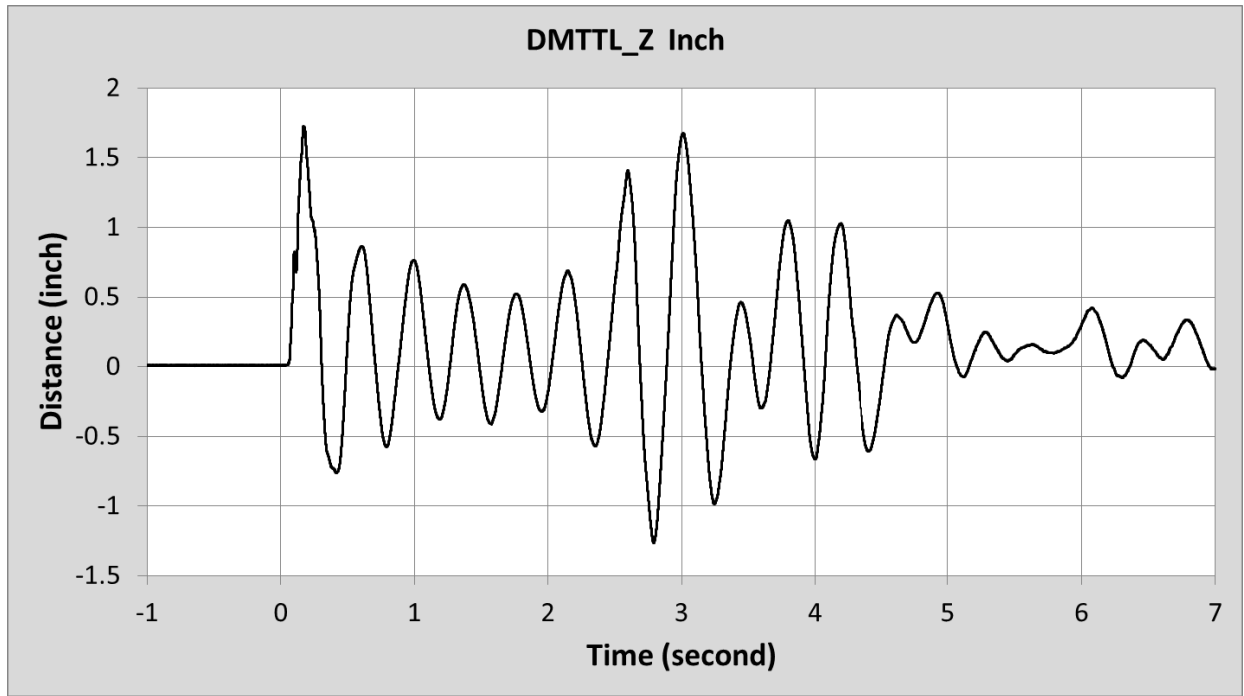


Figure F50. DMTTL_Z String Potentiometer Data

Appendix G.

12 mph Test Data

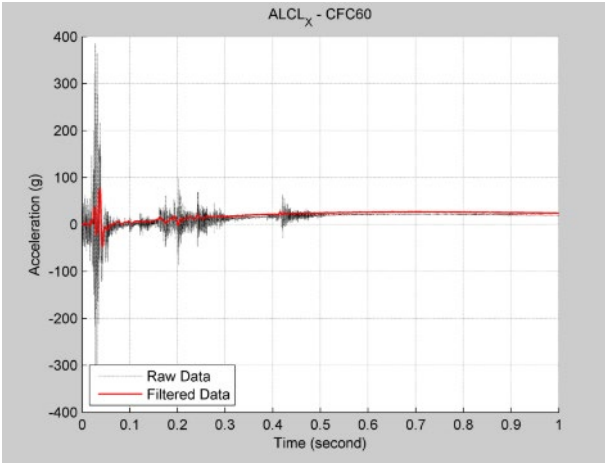


Figure G1. ALCL_X Accelerometer Data

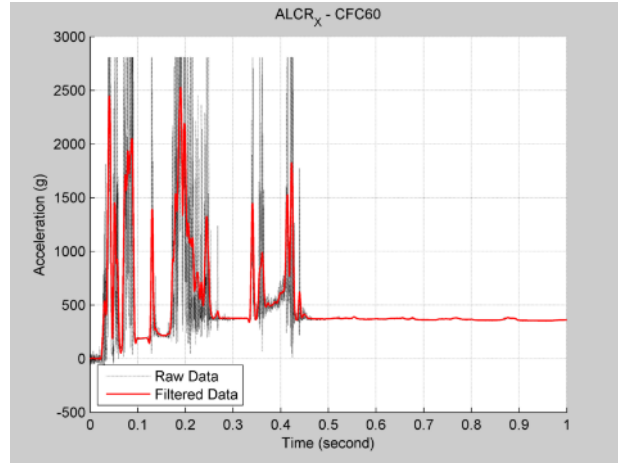


Figure G2. ALCR_X Accelerometer Data

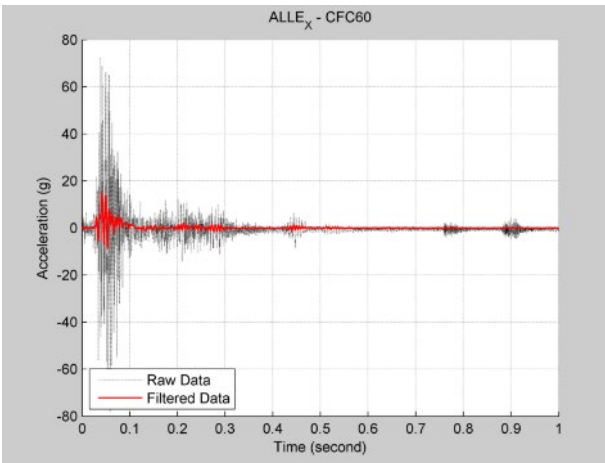


Figure G3. ALLE_X Accelerometer Data

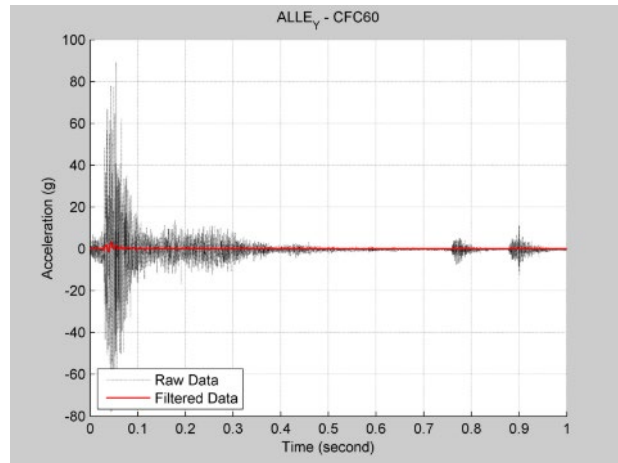


Figure G4. ALLE_Y Accelerometer Data

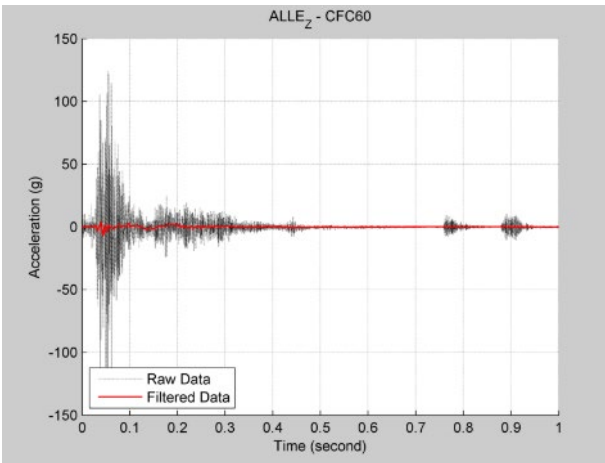


Figure G5. ALLE_Z Accelerometer Data

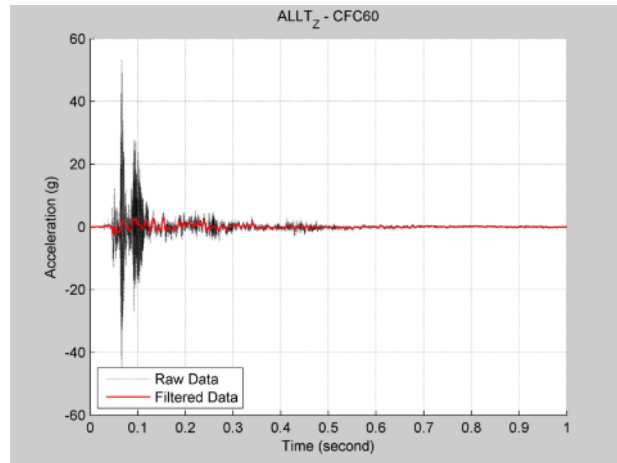


Figure G6. ALLT_Z Accelerometer Data

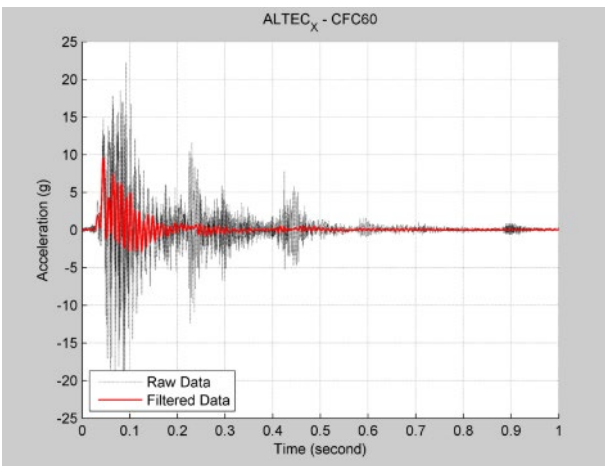


Figure G7. ALTEC_X Accelerometer Data

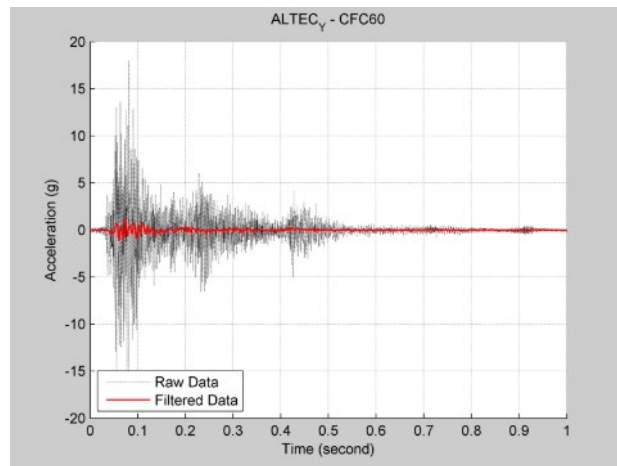


Figure G8. ALTEC_Y Accelerometer Data

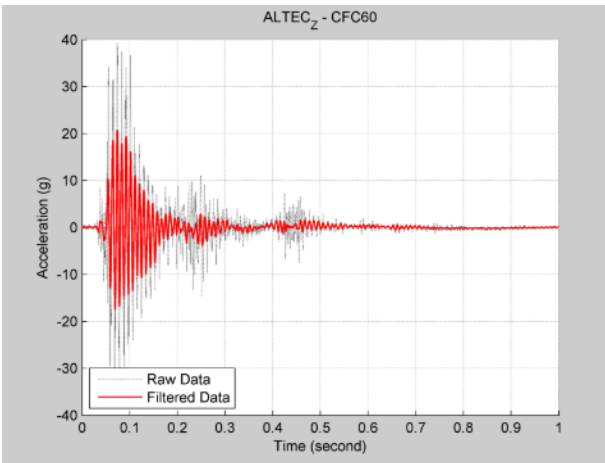


Figure G9. ALTEC_Z Accelerometer Data

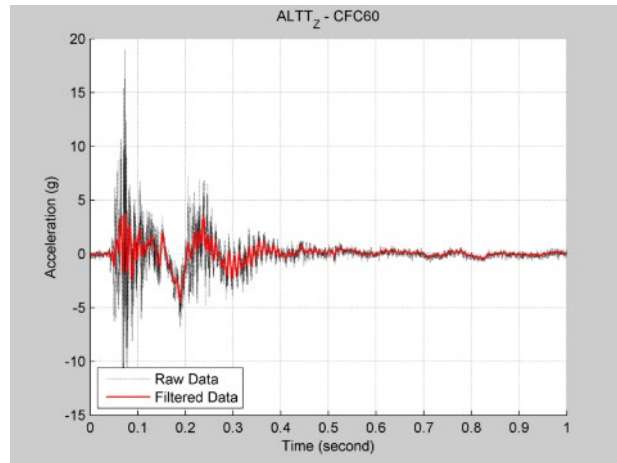


Figure G10. ALTT_Z Accelerometer Data

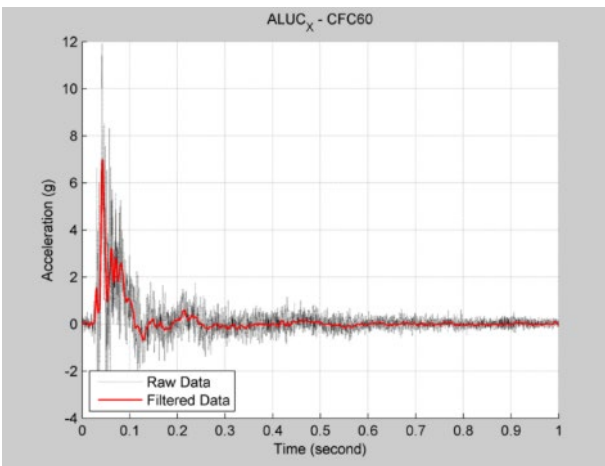


Figure G11. ALUC_X Accelerometer Data

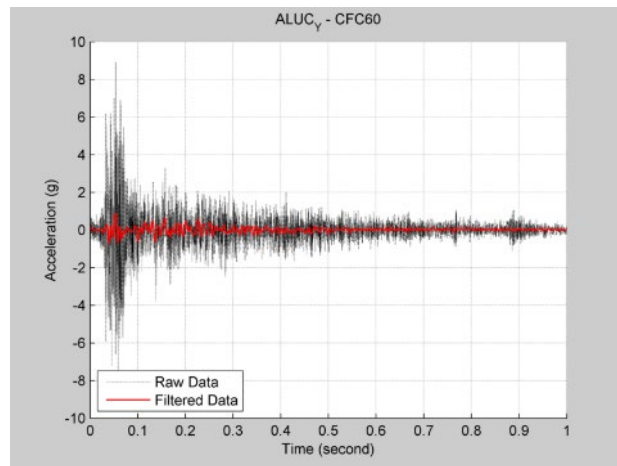


Figure G12. ALUC_Y Accelerometer Data

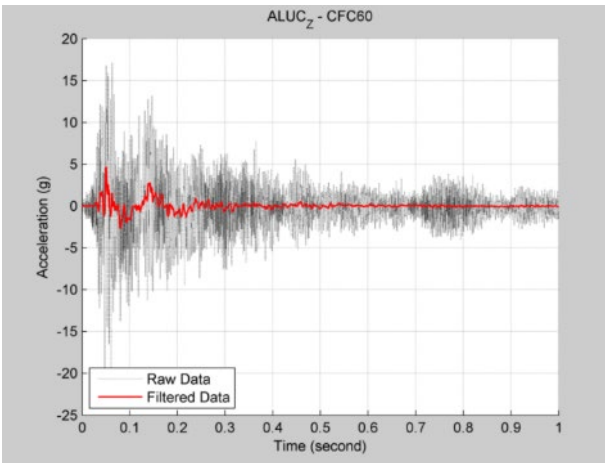


Figure G13. ALUC_Z Accelerometer Data

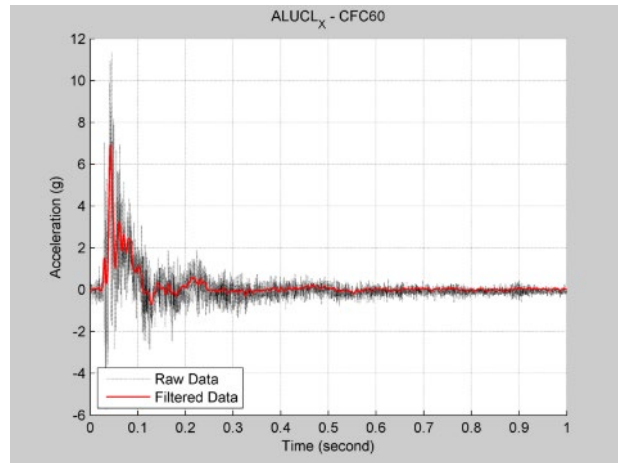


Figure G14. ALUCL_X Accelerometer Data

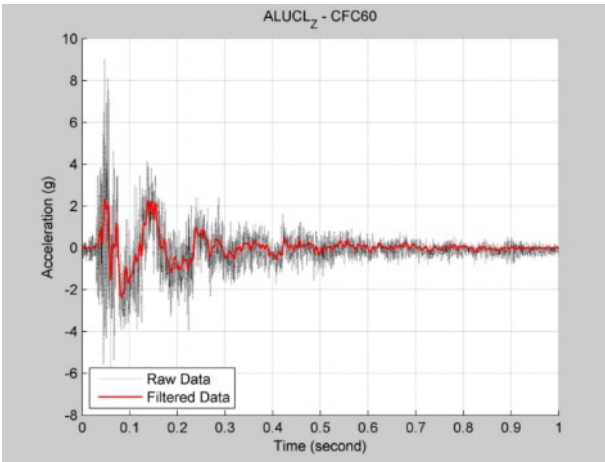


Figure G15. ALUCL_Z Accelerometer Data

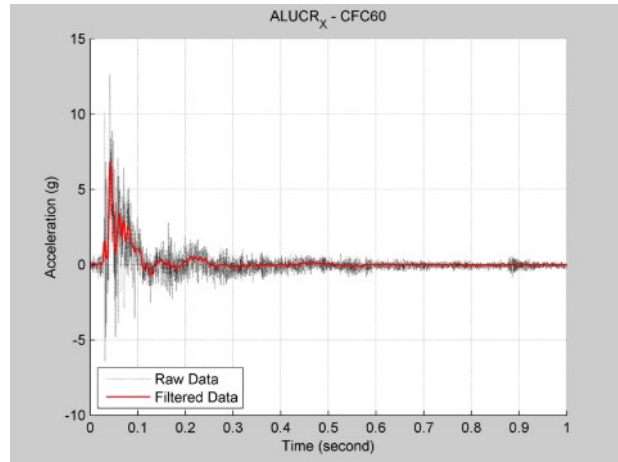


Figure G16. ALUCR_X Accelerometer Data

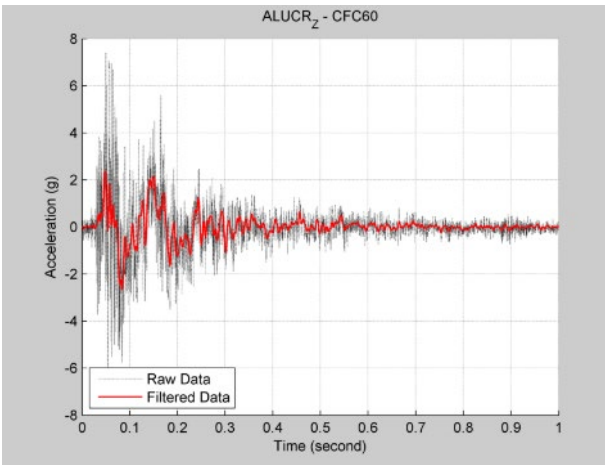


Figure G17. ALUCR_Z Accelerometer Data

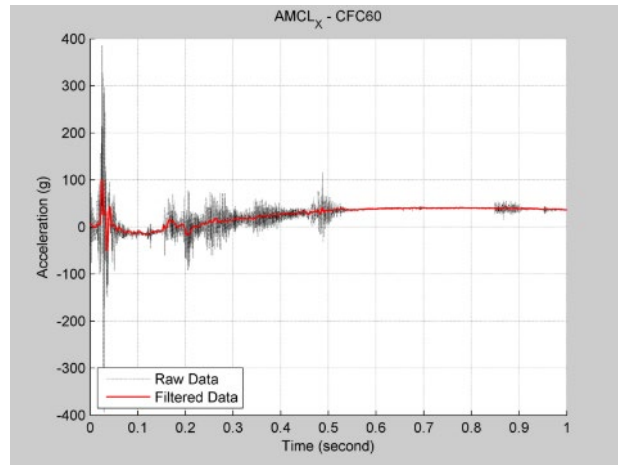


Figure G18. AMCL_X Accelerometer Data

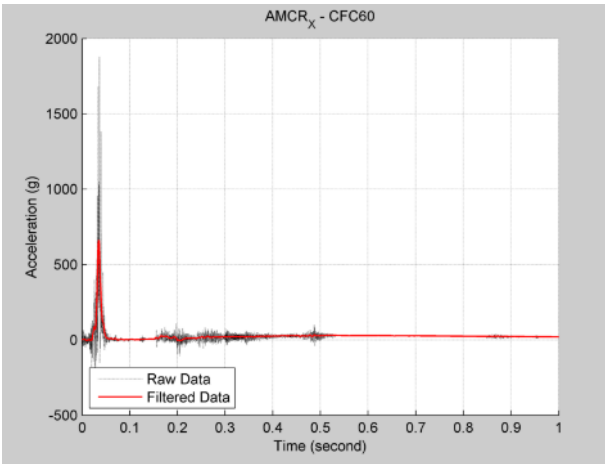


Figure G19. AMCR_X Accelerometer Data

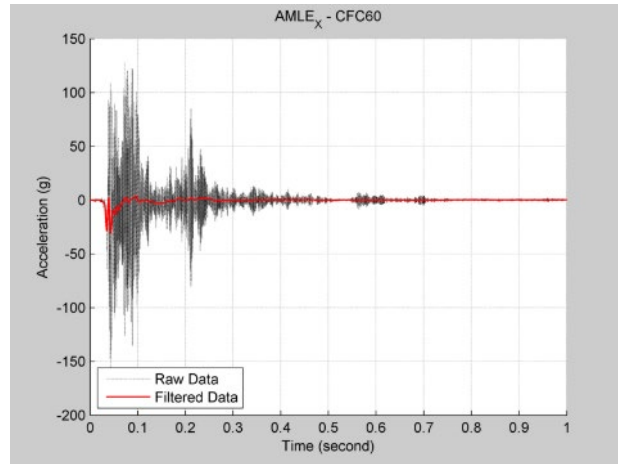


Figure G20. AMLE_X Accelerometer Data

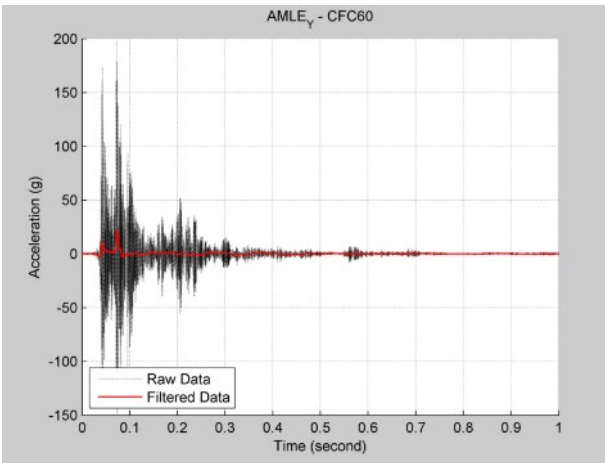


Figure G21. AMLE_Y Accelerometer Data

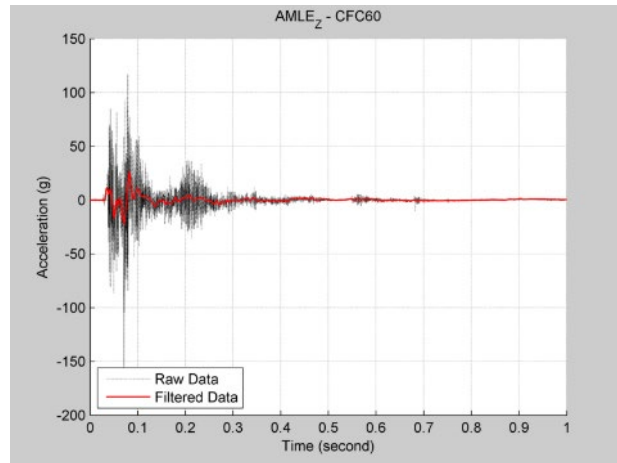


Figure G22. AMLE_Z Accelerometer Data

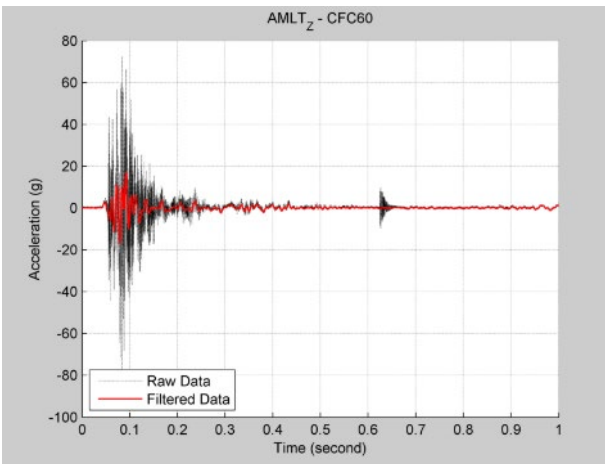


Figure G23. AMLT_Z Accelerometer Data

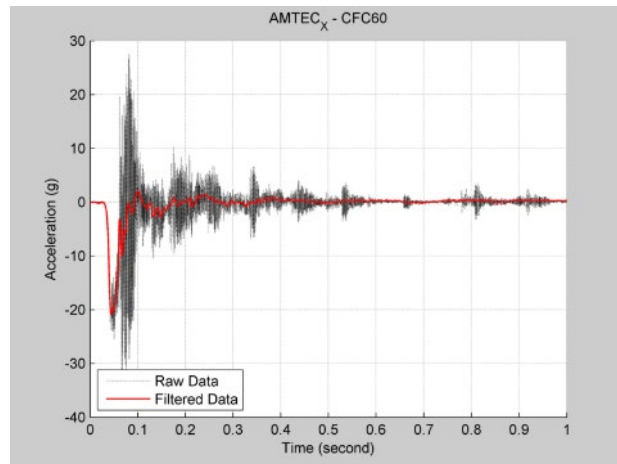


Figure G24. AMTEC_X Accelerometer Data

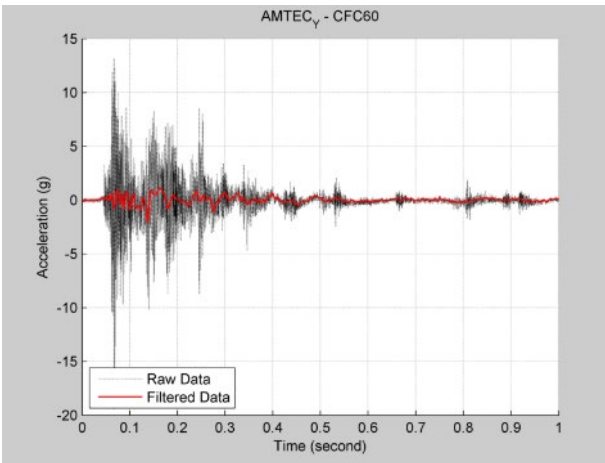


Figure G25. AMTEC_Y Accelerometer Data

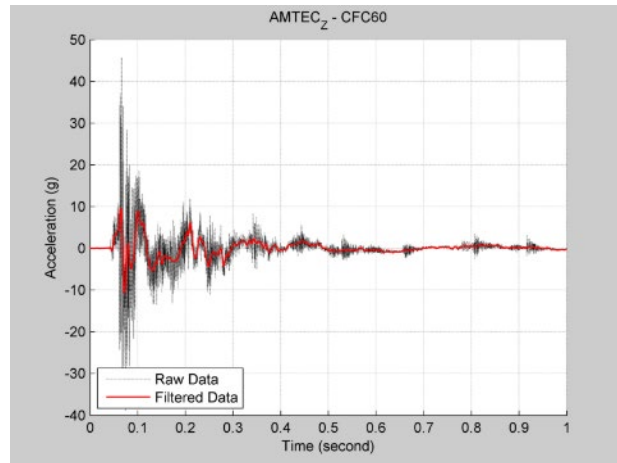


Figure G26. AMTEC_Z Accelerometer Data

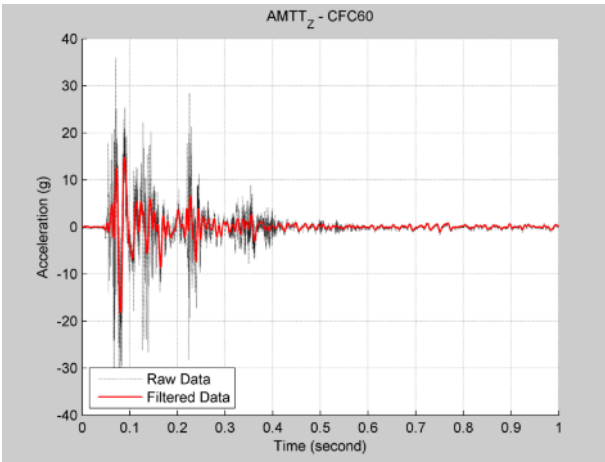


Figure G27. AMTT_Z Accelerometer Data

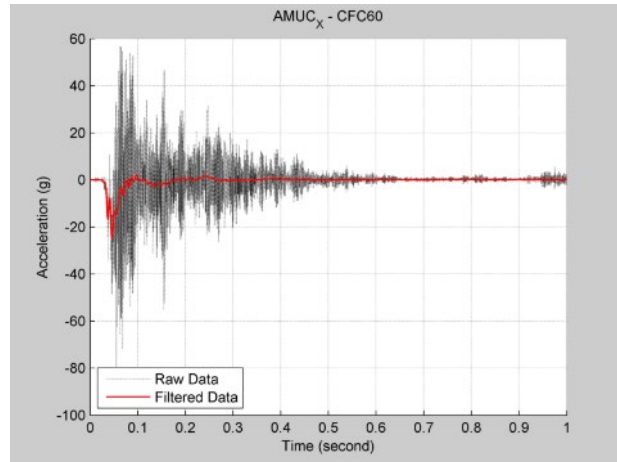


Figure G28. AMUC_X Accelerometer Data

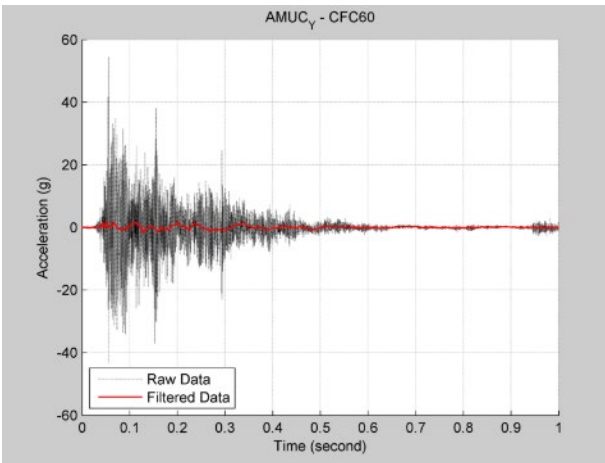


Figure G29. AMUC_Y Accelerometer Data

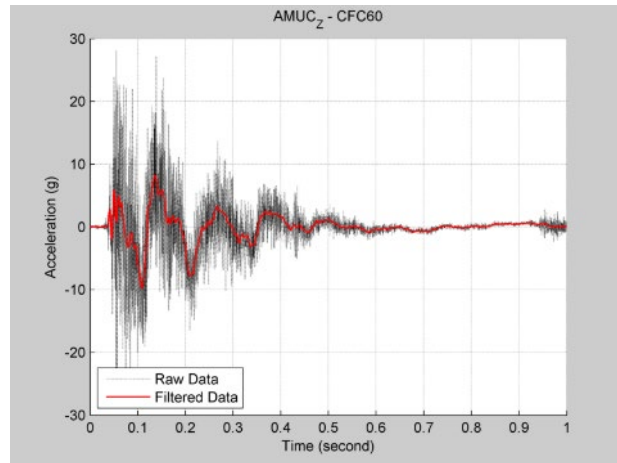


Figure G30. AMUC_Z Accelerometer Data

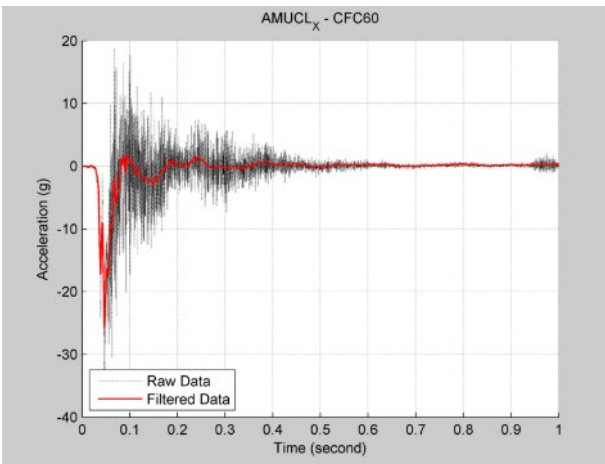


Figure G31. AMUCL_X Accelerometer Data

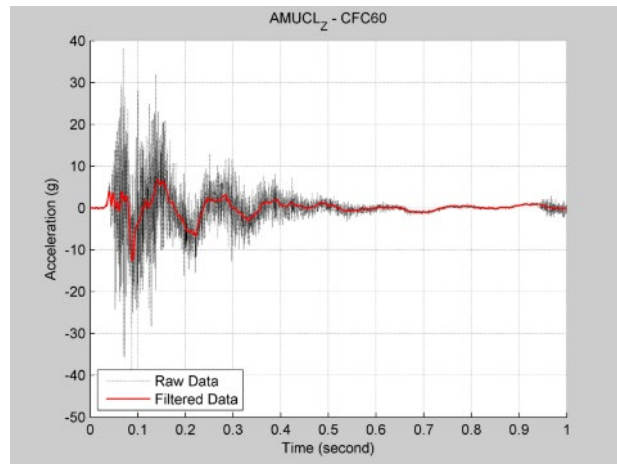


Figure G32. AMUCL_Z Accelerometer Data

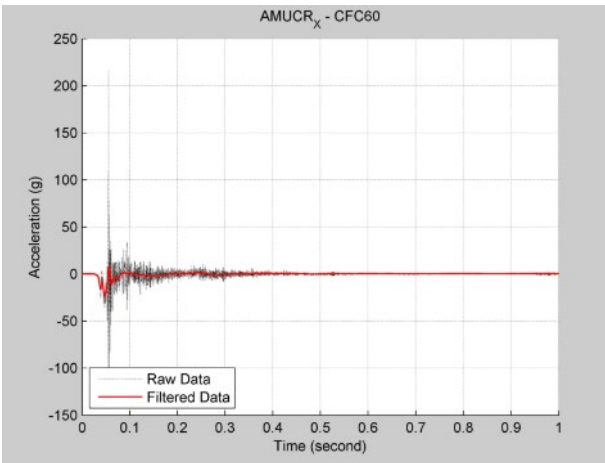


Figure G33. AMUCR_X Accelerometer Data

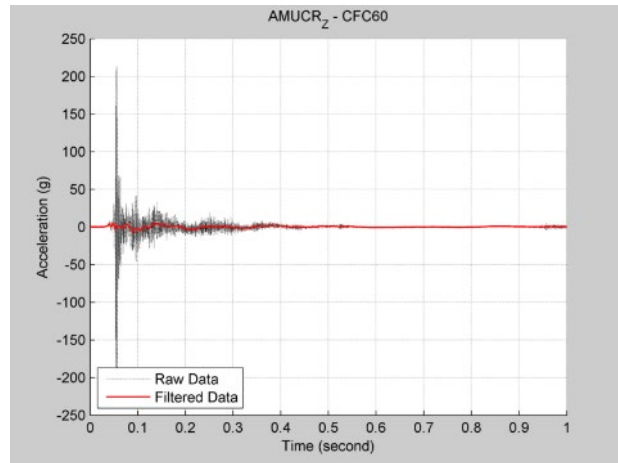


Figure G34. AMUCR_Z Accelerometer Data

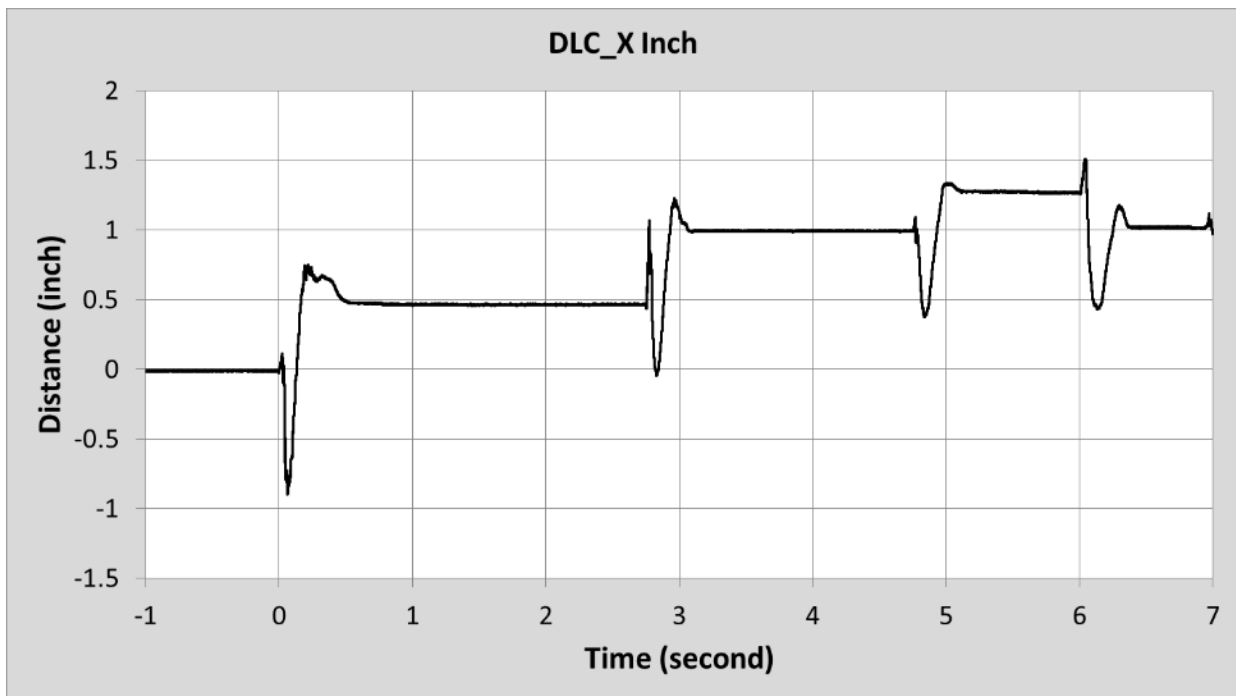


Figure G35. DLC_X String Potentiometer Data

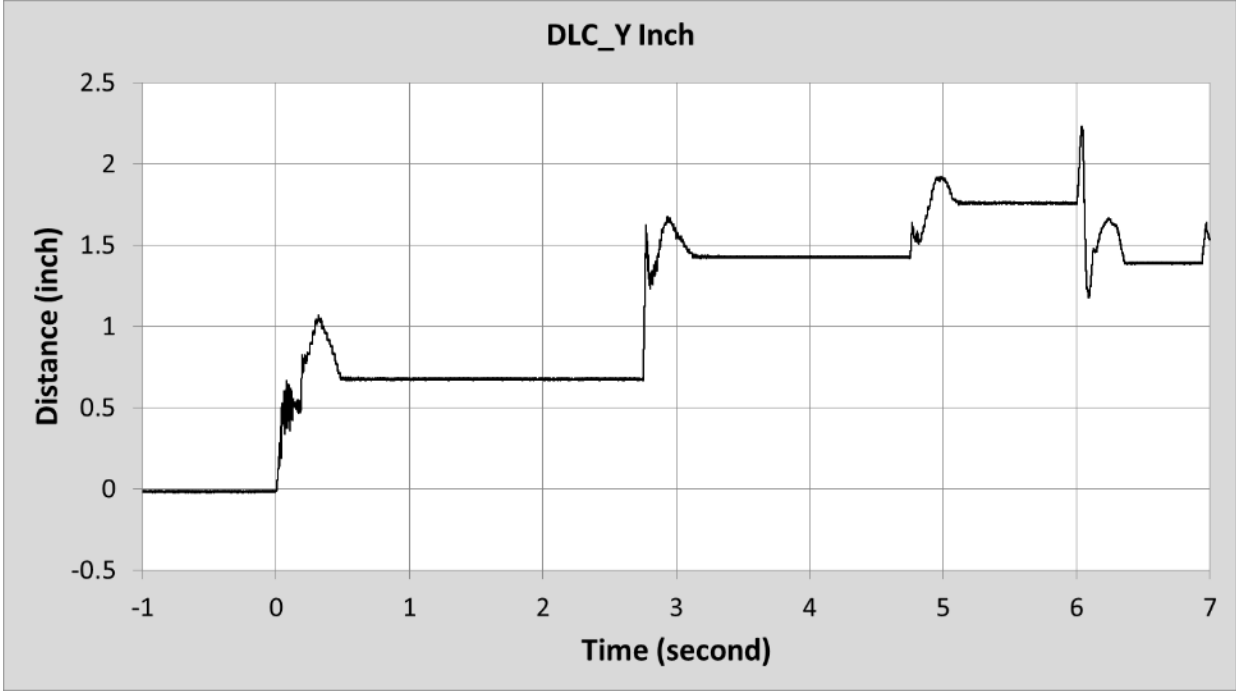


Figure G36. DLC_Y String Potentiometer Data

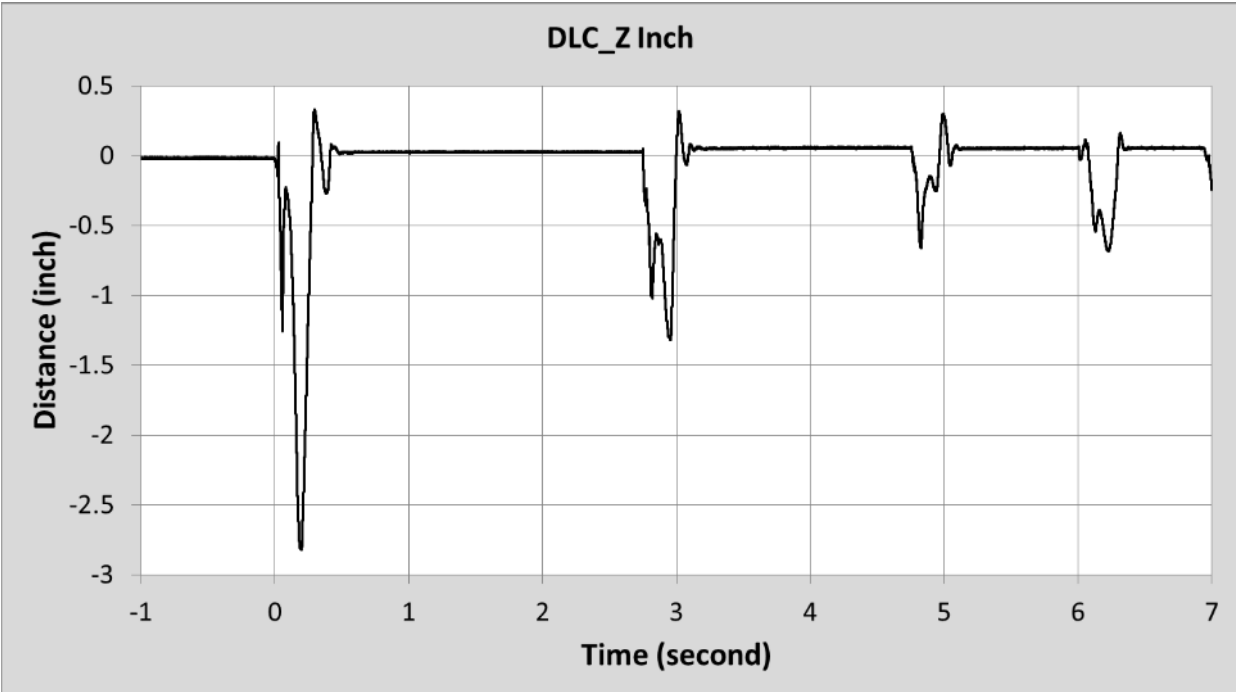


Figure G37. DLC_Z String Potentiometer Data

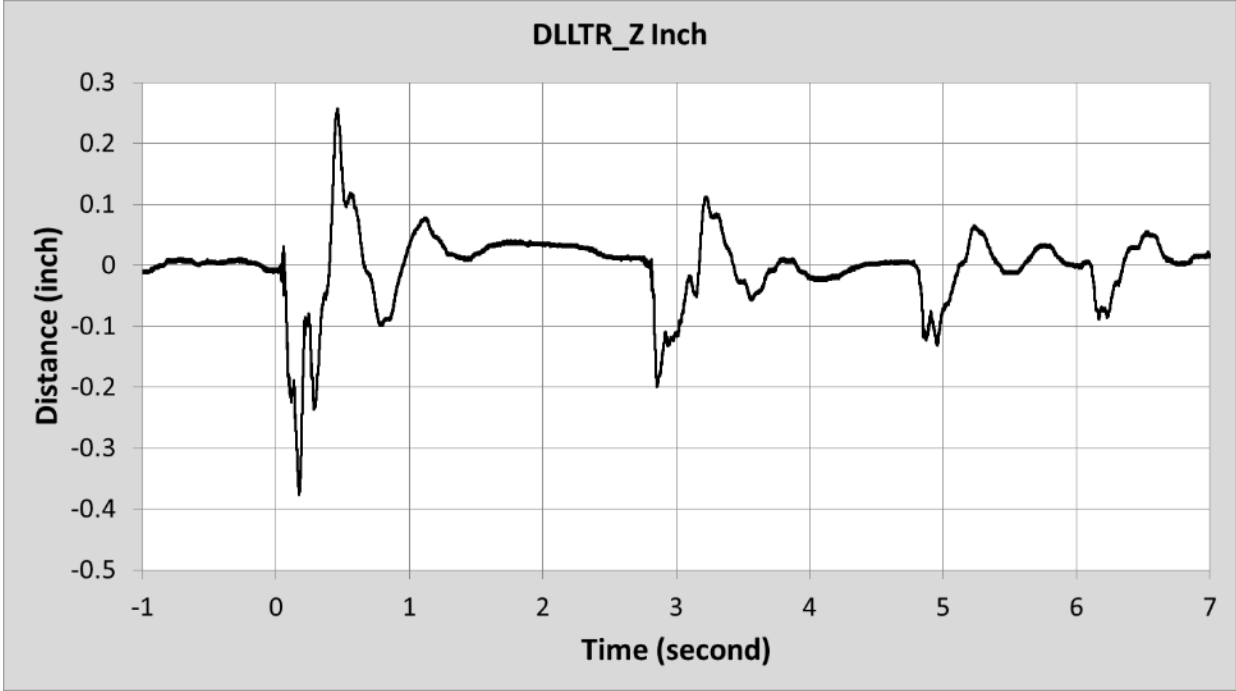


Figure G38. DLLTR_Z String Potentiometer Data

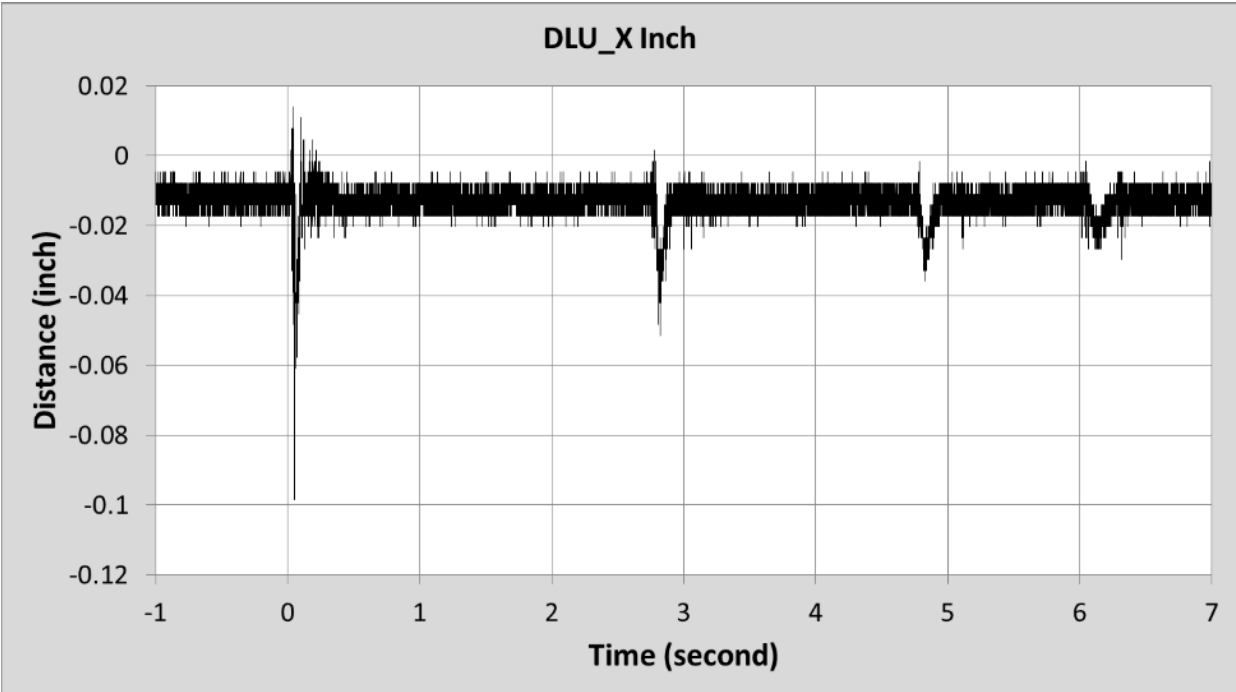


Figure G39. DLU_X String Potentiometer Data

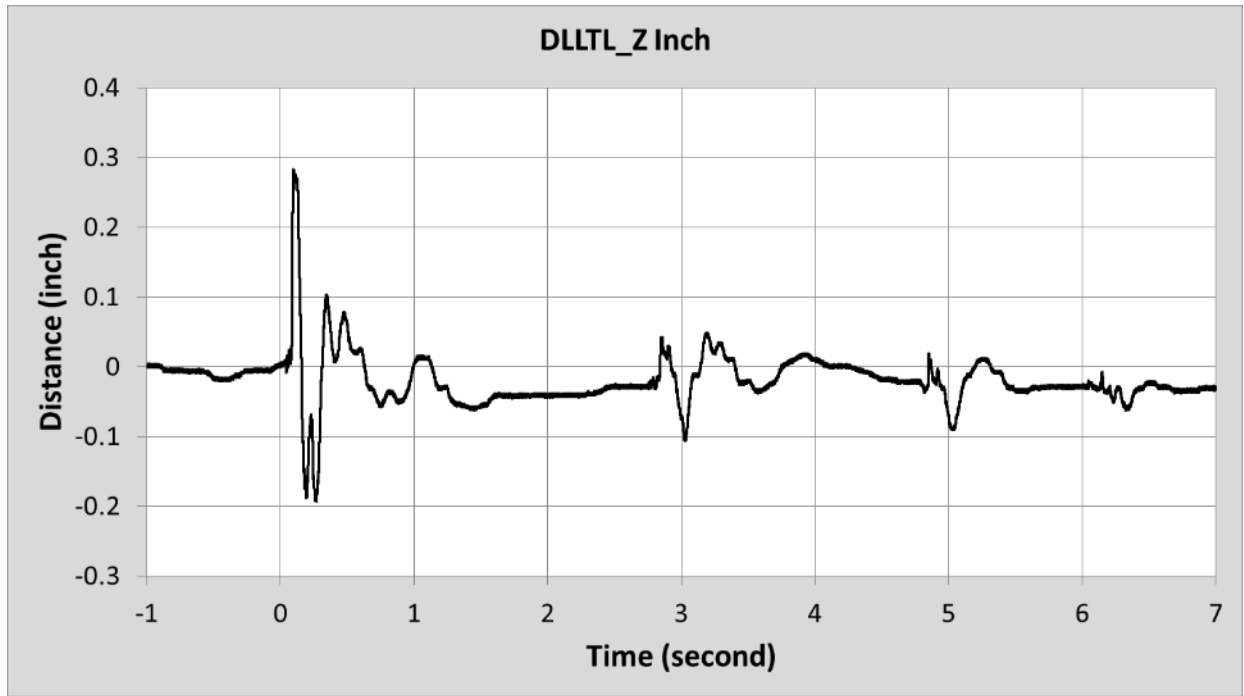


Figure G40. DLLTL_Z String Potentiometer Data

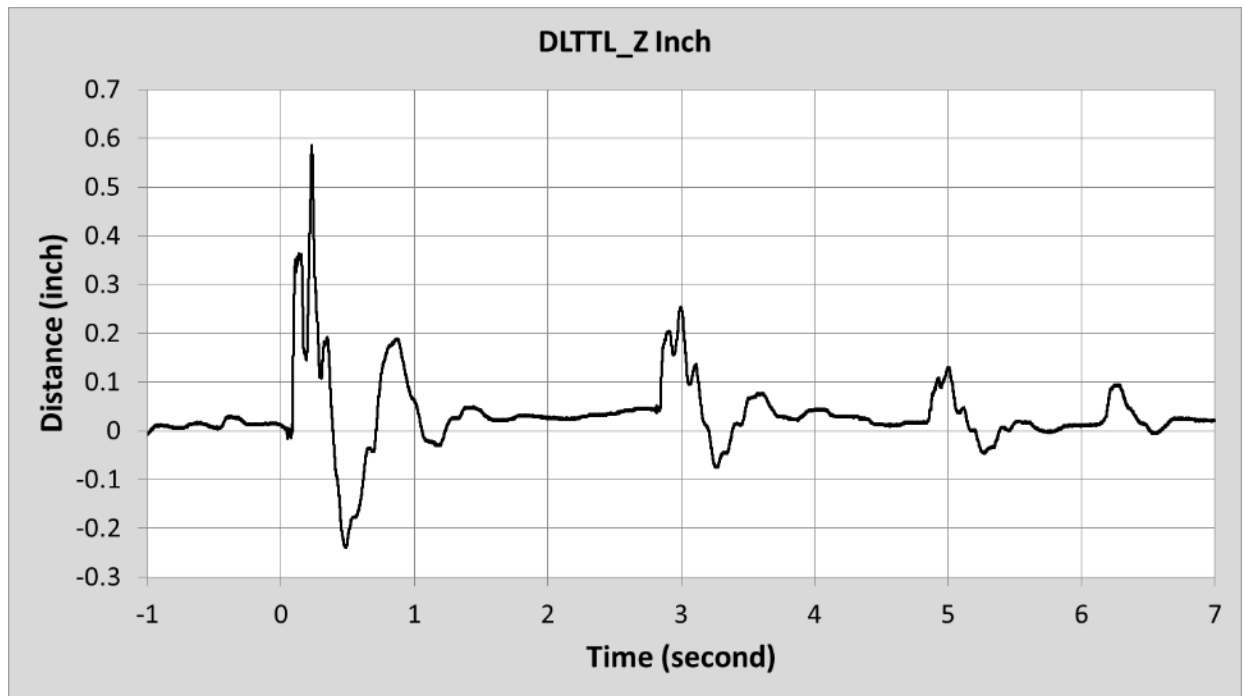


Figure G41. DLTTL_Z String Potentiometer Data

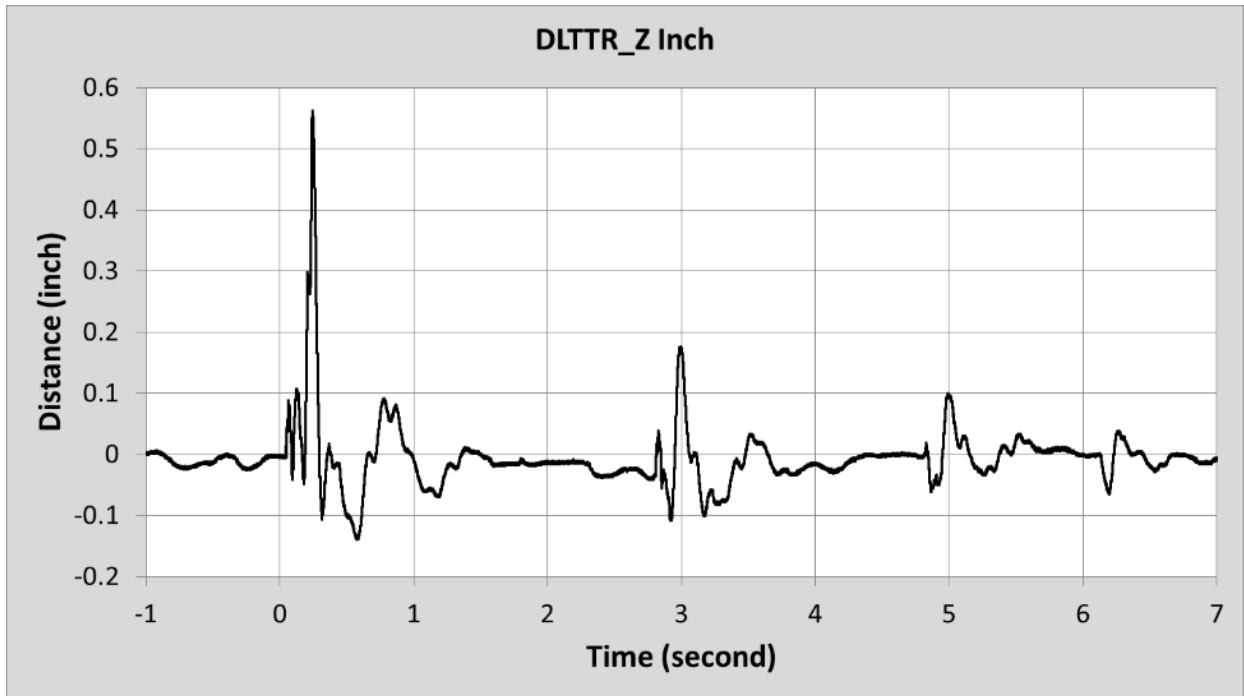


Figure G42. DLTTR_Z String Potentiometer Data

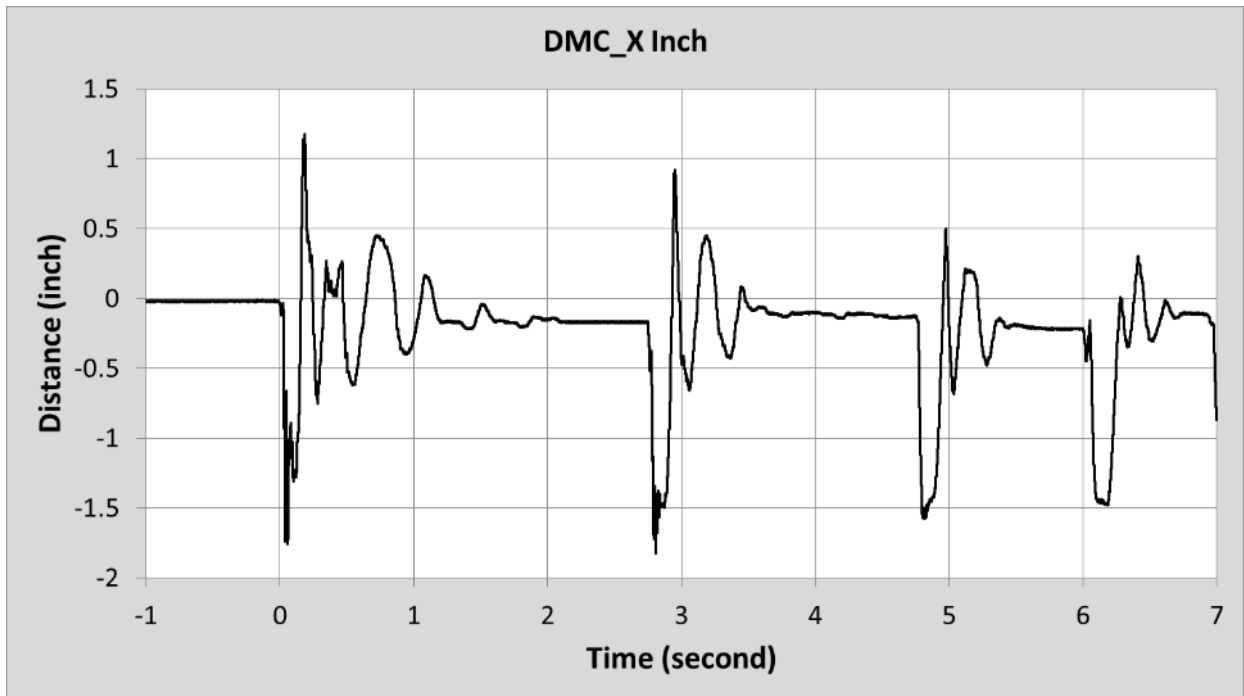


Figure G43. DMC_X String Potentiometer Data

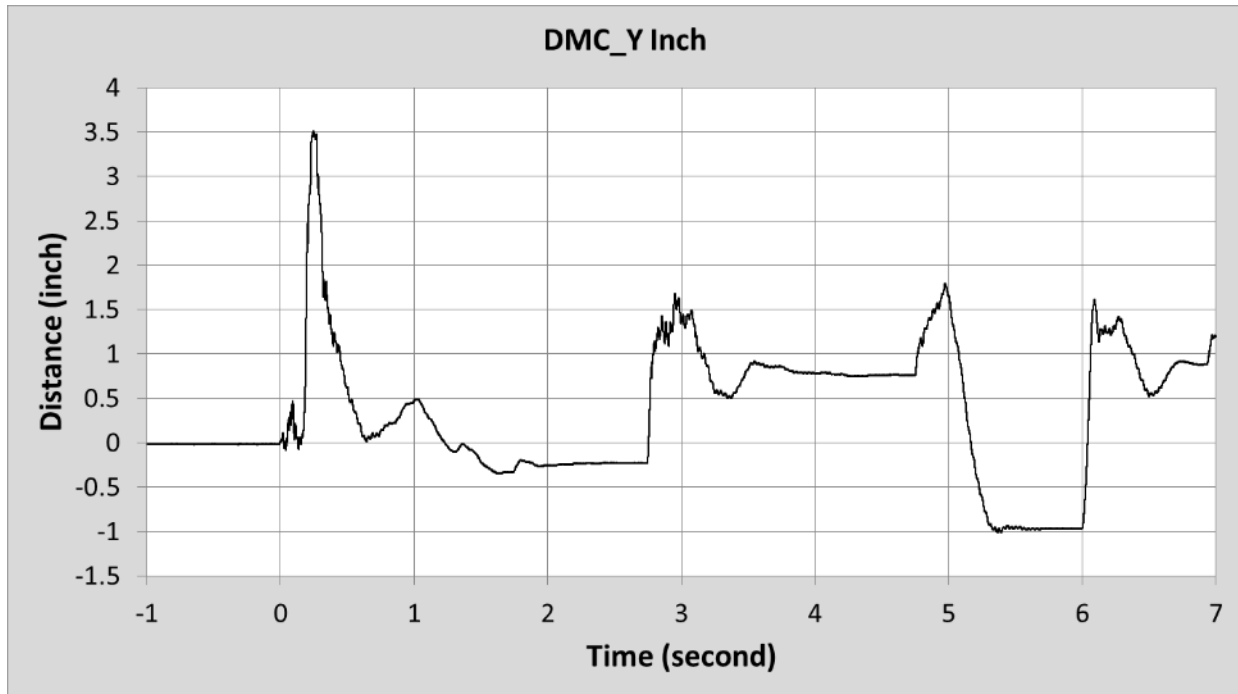


Figure G44. DMC_Y String Potentiometer Data

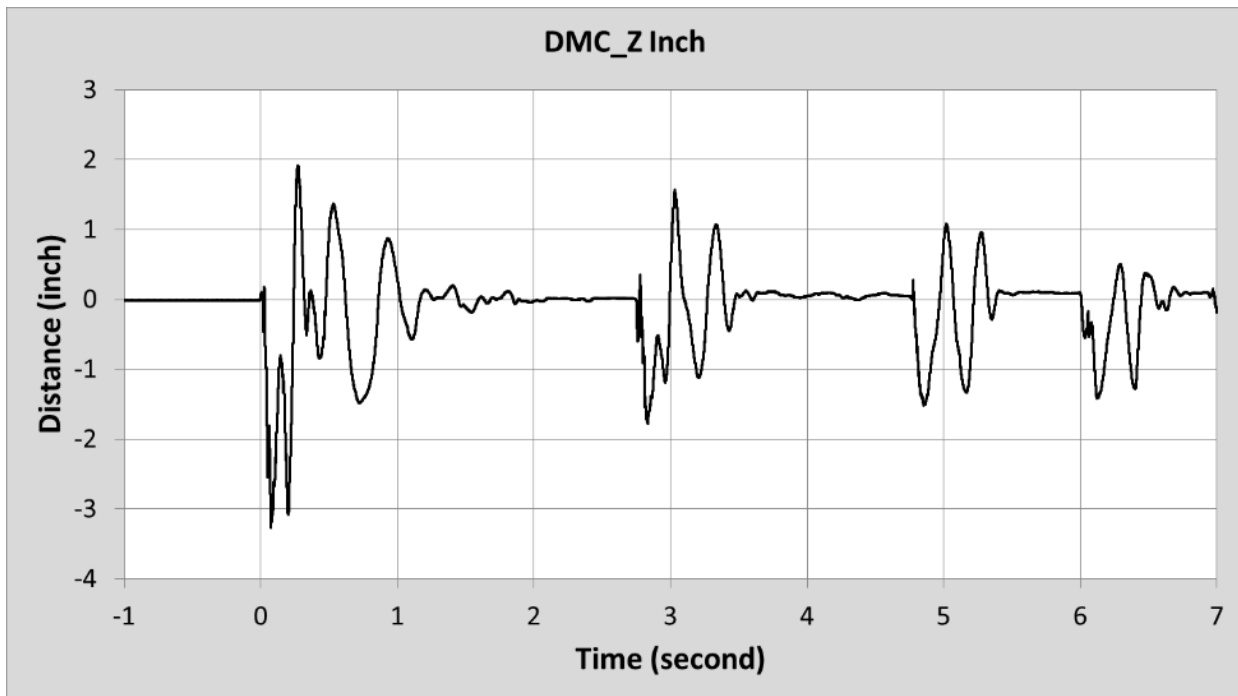


Figure G45. DMC_Z String Potentiometer Data

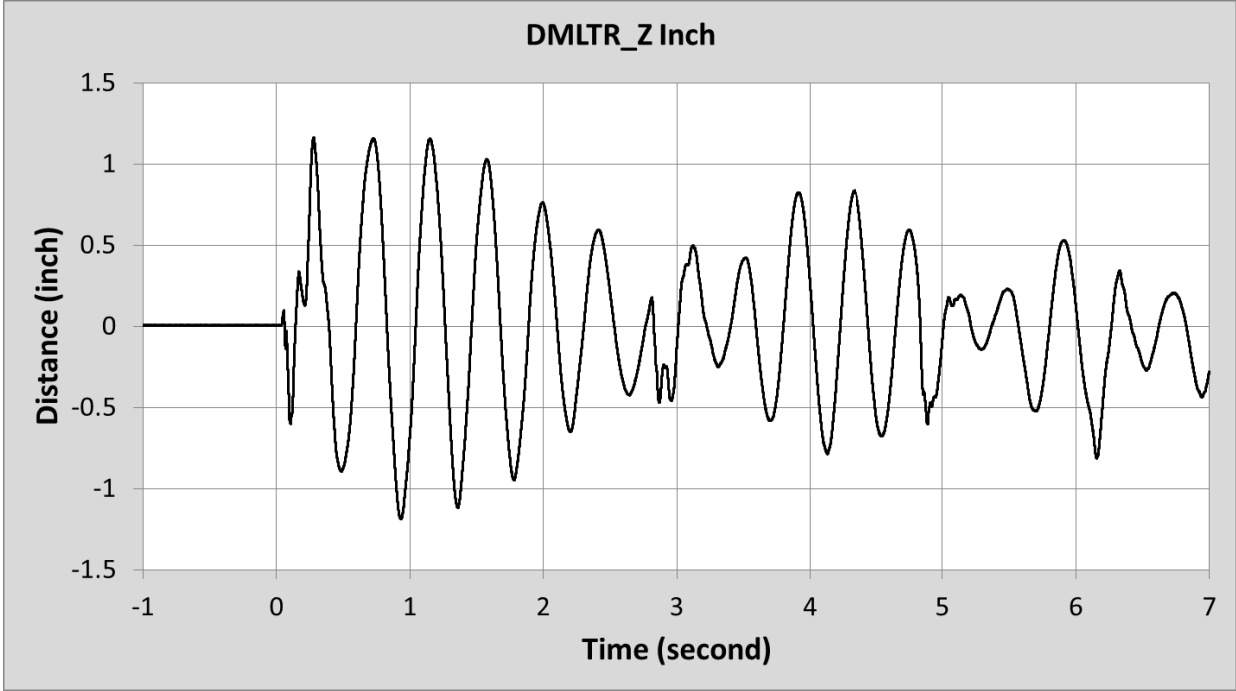


Figure G46. DMLTR_Z String Potentiometer Data

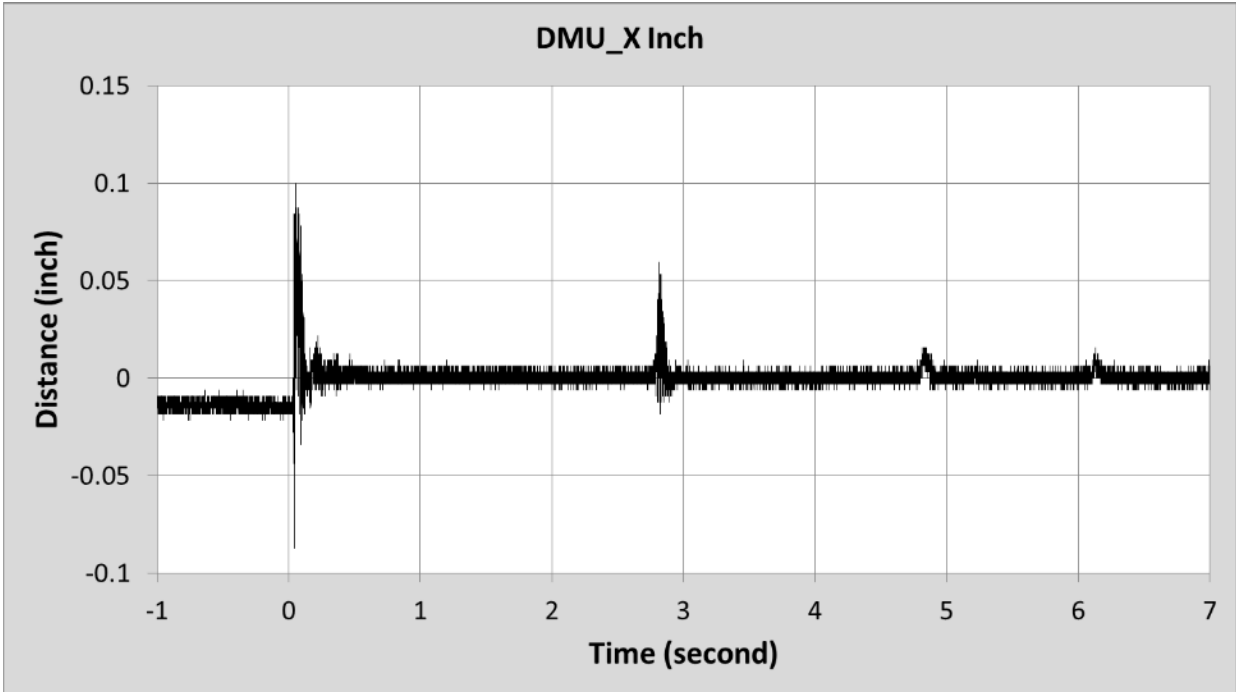


Figure G47. DMU_X String Potentiometer Data

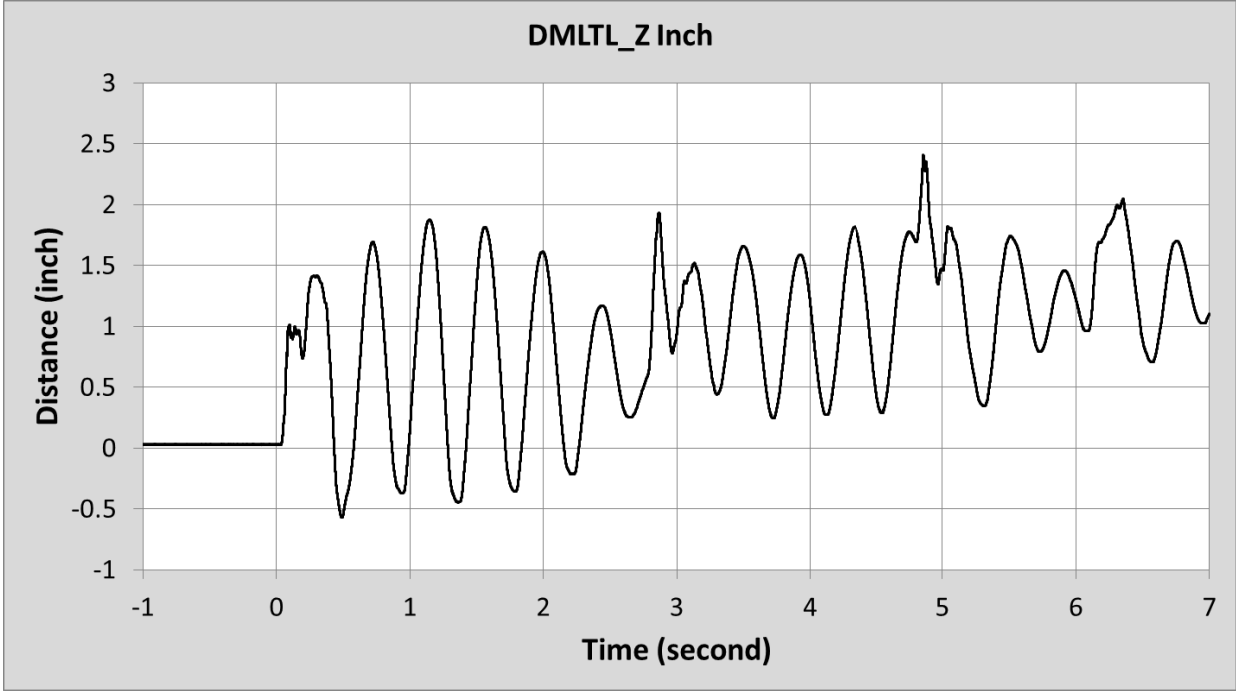


Figure G48. DMLTL_Z String Potentiometer Data

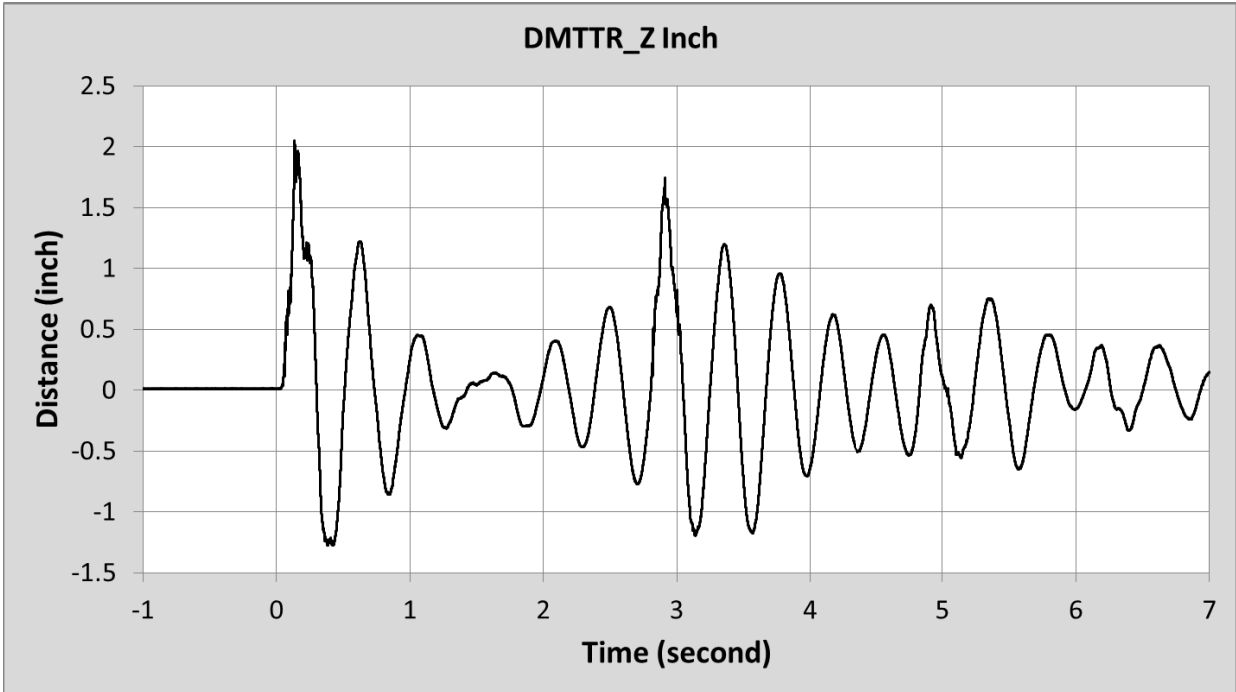


Figure G49. DMTTR_Z String Potentiometer Data

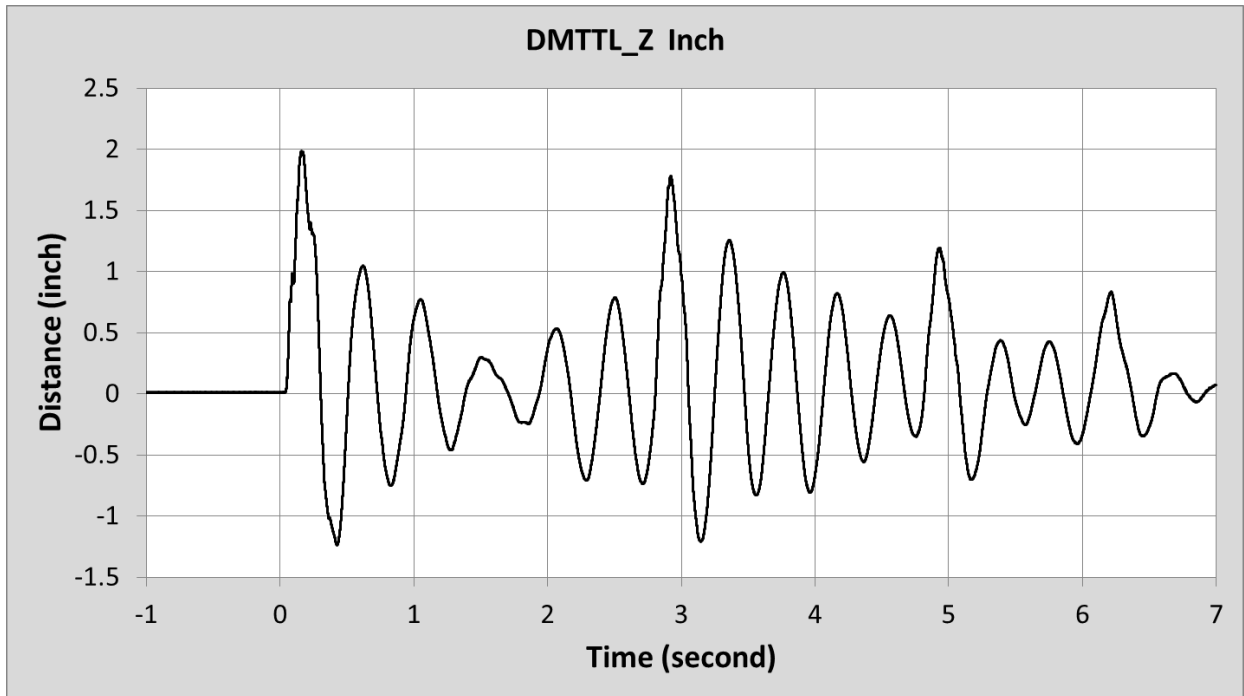


Figure G50. DMTTL_Z String Potentiometer Data