POTENTIOMETERS FOR MEASURING MICROINCH CRACK DISPLACEMENTS WITH WIRELESS SYSTEMS

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ABSTRACT

This paper describes qualification of devices to measure sub micro-meter changes in crack width, which is the basis of autonomous crack monitoring for control of blasting vibrations. Performance of LVDT, eddy current and potentiometer sensors to monitor long-term and transient displacements will be described. Potentiometers are attractive for wireless measurement, which is important as future autonomous crack displacement measurement almost certainly will be wireless. Long-term performance in the laboratory and the field is described in terms of drift, hysteresis, and noise upon exposure to cyclic changes in displacement and temperature. Transient performance is described in terms of relative response of the three systems to impact induced displacements with eddy current and LVDT serving as the benchmark.

INTRODUCTION

This paper summarizes qualification testing of string potentiometers for measuring sub micro-meter changes in crack width or displacement. Potentiometer displacement sensors do not require a warm-up interval and thus draw little power. As a result, they are attractive for wireless measurement, which is important as future field measurement systems almost certainly will be wireless. Potentiometers measure displacement through rotation of a spring-loaded drum. While this system is thought to have little influence on the long term, quasi-static changes in crack width, it has its own dynamic response. Thus in addition to the usual qualification tests needed to ensure low noise, drift, and hysteresis during long-term surveillance, and investigation of potentiometers also required development of a qualification method to determine their dynamic response characteristics. Procedures to qualify potentiometer performance should be similar to those for the more traditional, high power drawing LVDT and eddy current sensors. (Dowding and Siebert, 2000)

Any instrument that must endure cyclic temperature and humidity over long periods of time must maintain a constant relation between its output and the parameter being measured. Thus it cannot drift or have a large hysteretic response. Furthermore its noise level must be less than typical variations of the parameter being measured. Before proceeding it is important to define these three parameters with respect to measurement of micro inch crack displacement.

Linearity of the sensor output with respect to cyclic variations in displacements is one of the major factors that determine the accuracy of that sensor output. The ideal transducer is one whose output is exactly proportional to the variable it measures within the sensor's quoted range. Hysterisis is the difference in the output of the sensor at the same temperature during one expansion-contraction cycle of the material to which the sensors are attached. Obviously, the sensors that have smaller hysteretic bandwidths have greater resolution. Importance of hysterisis is amplified by cyclic temperature environment that accompanies and induces the change in the displacement measured by the sensor.

Electronic drift is another challenge posed by long-term measurements cyclically varying temperature environment. It is important that there be no to little instrument drift during crack response to cyclic environmental change over long periods of time. Drift can be explained by major changes or shifts in the sensor output over time at the same crack width. The only change in output of with time should be caused by the displacements of the crack.

In addition to the laboratory qualification testing of the potentiometer, responses of the potentiometer and an LVDT mounted across the same crack in a test house were compared. This field test was devised to assess the performance of the potentiometer in field conditions while subjected to blast induced crack and structure response.

EXPERIMENTAL SETUP

Two different mechanisms were designed in to simulate the effect of field conditions that are responsible for crack width change, which in turn produce sensor response. Several field conditions were simulated. First, the system was subjected cyclic temperature variations, which cause crack opening and closing due to expansion and contraction of the walls. Long-term qualification tests involve sensor measurements of temperature induced cyclic expansion, and expansion/contraction of two types of expandable materials. Second, the system was subjected to dynamic displacements. This transient displacement qualification test involved sensor measurements of change in separation of two aluminum blocks subjected to impact loading.

A SpaceAgeControl type 150 potentiometer was chosen for evaluation because of its small size, low energy consumption and no warm-up time, which is advantageous in the wireless sensor network projects. FIG. 1 shows a close-up view of one of potentiometers with the wireless system embedded in the forest of connections of the wired system. A potentiometer sensor consists of a stainless steel extension cable wound on a threaded drum that is coupled to a precision rotary sensor. Operationally, the position transducer is mounted in a fixed position and the extension cable is attached to a moving object. The axes of linear movement for the extension cable and moving object are aligned with each other. As movement occurs, the cable extends and retracts from an internal spring that maintains tension on the cable. The threaded drum rotates a precision rotary sensor that produces an electrical output proportional to the cable travel.

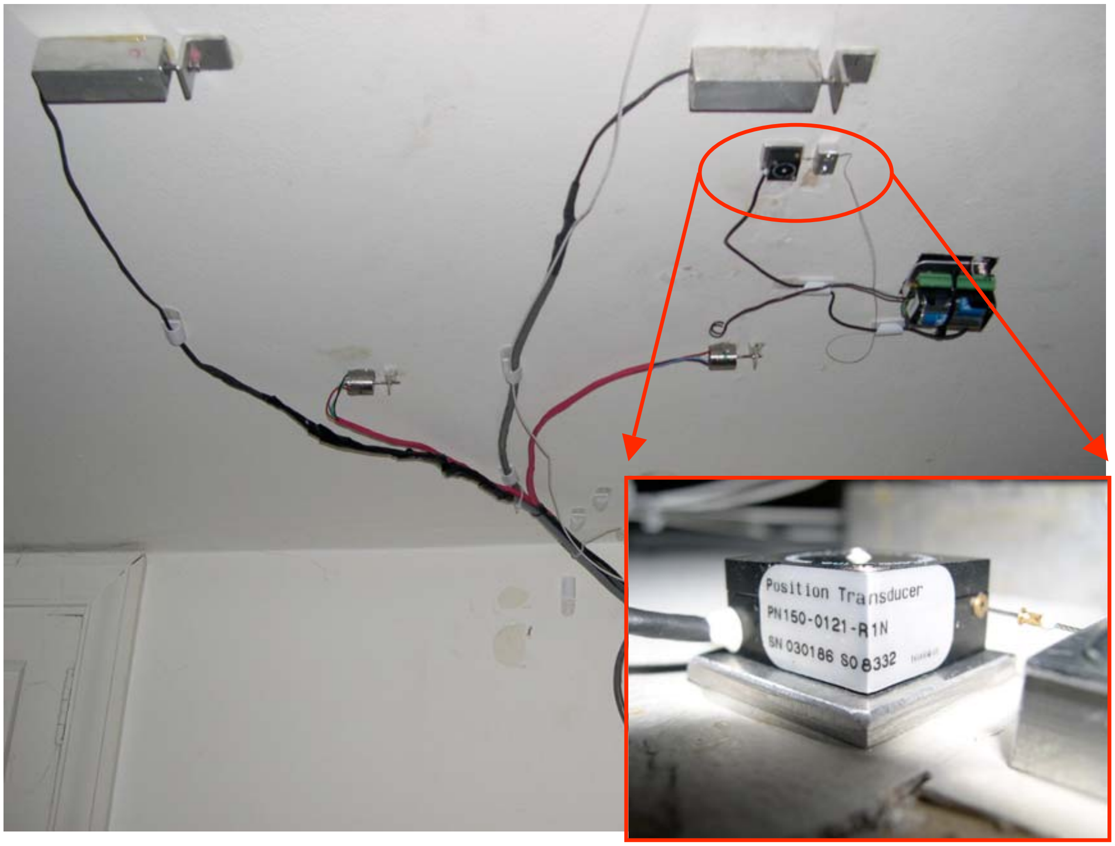

FIG. 1. Potentiometer across a ceiling crack with the wireless network

Long-term qualification

The most simple system involves attaching the sensors to a plate of material that expands and contracts with a known thermal expansion. The potentiometer and a comparative DC 750-050 LVDT were glued close together on both aluminum and PE-UHMW plastic plates to respond to similar thermal expansion and contraction during cyclically changing temperatures. Temperature on the plates was measured with a thermocouple between the sensors. SOMAT 2100 (Somat, 2005) stacks collected the sensor and thermocouple measurements. The traction on the boundaries of the plates was minimized in order to have homogeneous thermal strains on the plate surface.

FIG. 2 shows the configuration of another long-term test, which will be referred as “donut” test. In this case the hollow cylindrical material, which is a PE-UHMW, was glued between each of the sensors and their targets. Thermal expansion and contraction of the donut directly changed the opening and closing of the gap between the sensor and target. Thermocouples taped on the donut measured the cyclically changing temperatures of the polyethylene.

The potentiometer and comparative LVDT measured the expansion and contraction of the material to which they were glued during the plate test and that between the sensor body and its target during the donut test. LVDT sensors have been used in crack monitoring projects for many years and they are judged to be as reliable enough to validate the output of the potentiometer.

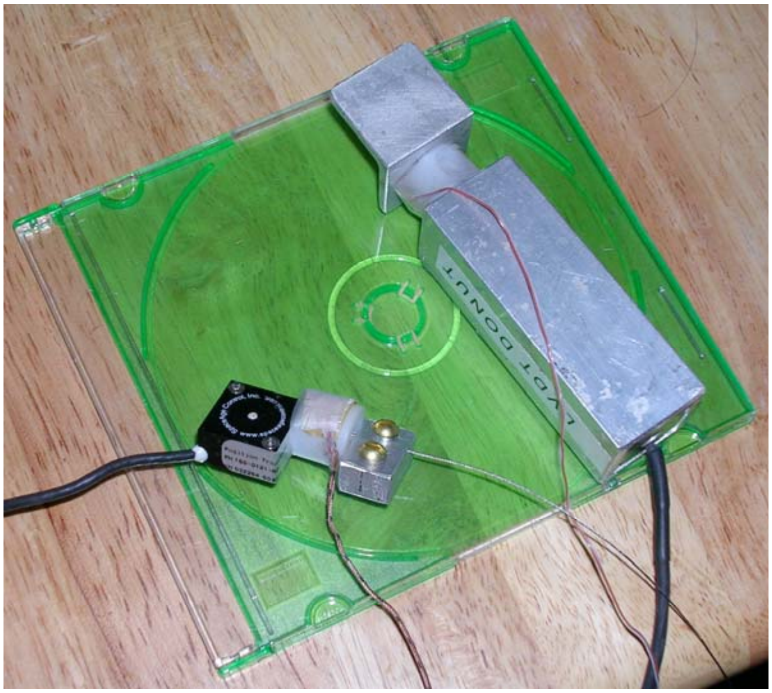

FIG. 2 Experimental setup from donut test

Dynamic qualification

Vibration induced transient crack opening and closing was simulated by applying impact loads on the top of aluminum two blocks shown in FIG. 3 that sandwich a thin rubber sheet. Concern about the effect of the inertia of the spring mechanism on the potentiometer measurement lead to development of this device, which was subsequently employed to compare responses of LVDT and eddy current devices as well.

FIG. 3 shows the test configuration to compare potentiometer and eddy current sensor response. The same test procedure was repeated with eddy current sensor and potentiometer sensor couples. In each test both sensor bodies were glued on the bottom plate at an equal distance from the centerline of the block whose displacements were restricted in the horizontal and vertical directions. Sensor targets were glued on the upper plate that should ideally move only in vertical direction. A thin rubber sheet was placed in between the aluminum blocks. Small dynamic vertical displacements of the upper block relative to the lower were produced by dropping a small weight on the upper block. Therefore the drop weight mechanism as shown in FIG. 3 was designed not only to have an adjustable drop height of the weight but also to allow loading at the center of the top face of the upper block. A weight of 0.22 kg (0.5 lbs) was dropped through a pipe at various heights to generate impact loading in the upper block. Although uniform displacement of the upper block was anticipated, either lack of horizontal support or difficulty of aligning the load with the center of gravity of the upper block caused a slight non-uniform displacement at the face of upper block. This slight deviation affected the magnitudes of the displacements measured by the sensors and caused an unknown variation of sensor output.

FIG. 3 A test mechanism to measure the transient response with LVDT (on the right) and potentiometer sensors (on the left)

In addition to the laboratory experiments, two potentiometer sensors were integrated with an ongoing project in a test house in Milwaukee to compare laboratory and field performance. As it is shown in FIG. 1, the potentiometer sensors are next to a LVDT sensor across the same ceiling crack. This house was subjected to ground vibrations from blasting in an adjacent quarry. The purpose of these measurements is to compare displacements measured by the potentiometer and the benchmark LVDT when subjected to the same dynamic crack responses.

ANALYSIS OF THE RESULTS

Long-term response

FIG. 4 shows the measured displacements and temperature variations during the aluminum plate and donut tests conducted by wireless network on the roof of a downtown building. As it can be seen from those trend figures, cyclic temperature variations causes the plate and donut expand and contract. Same kind of test was also conducted by the wired system whose results were employed to qualify the potentiometer by comparison to the benchmark sensors such as the LVDT.

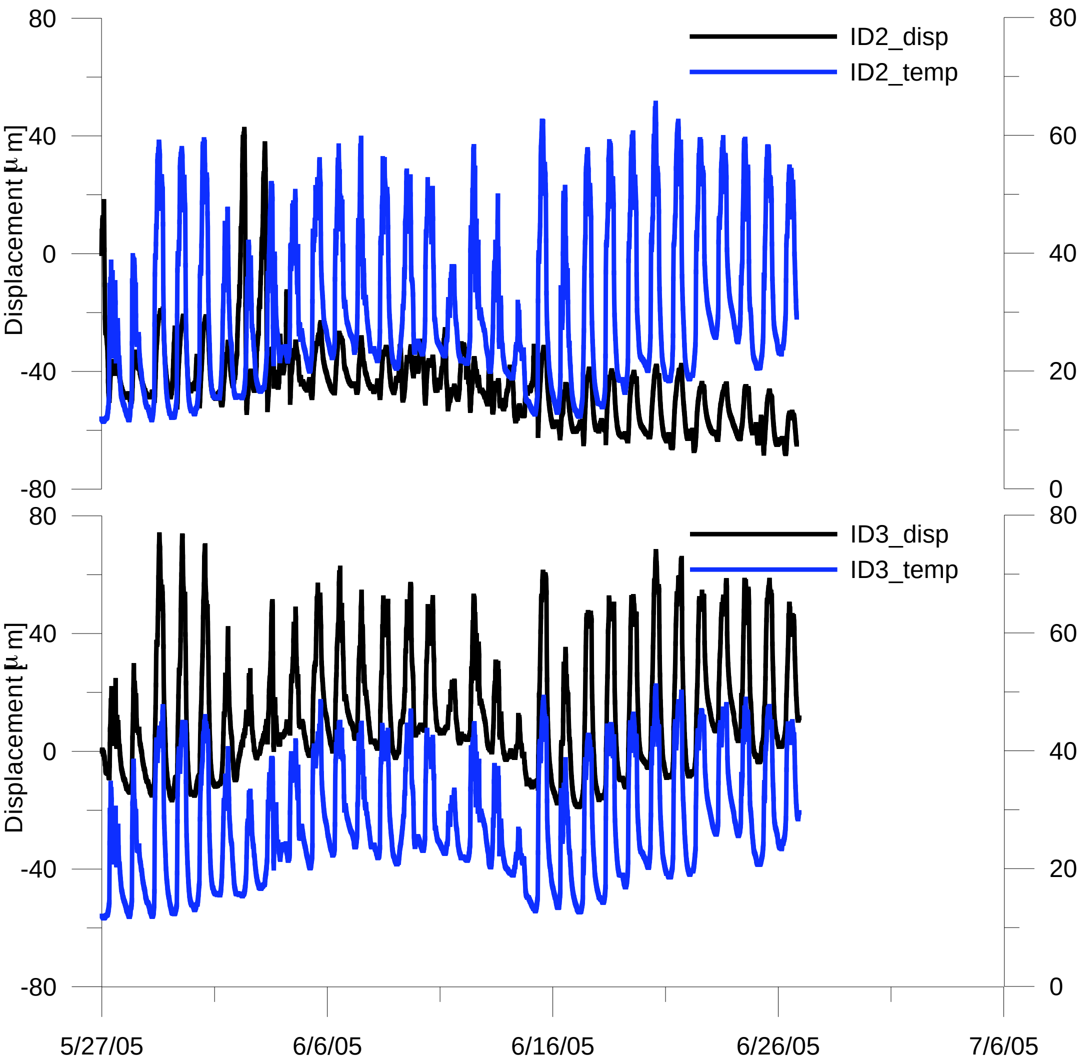

FIG. 4: Sensor displacements due to cyclically changing temperatures (measured by the multi-hop wireless network on the roof a downtown building)

FIG. 5 provides a comparison between potentiometer and LVDT during the plate and donut tests with wired system in an environment whose temperature variations are in a range between 10 to 32 ^{o}C. Except for the aluminum plate test, the displacements detected by the potentiometer are apparently smaller than the displacements measured by LVDT. Hysteretic loops for the LVDT are smaller than for the potentiometer.

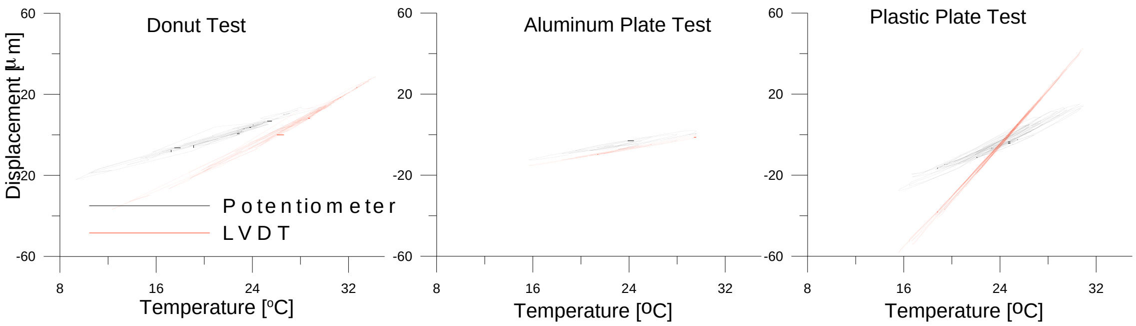

FIG. 5: Comparison of potentiometer and LVDT displacements from cyclically changing temperatures

Hysteretic bandwidth is a function of the accuracy of the sensors as well as how the plate or donut material behaves linearly with respect to cyclic temperature variations. A statistical measure of the goodness of the data can be defined by mean of the residuals divided by the difference between the two extreme values of the measured cumulative displacements, σ_1, standard deviation of the measured cumulative displacements (with respect to the regression line), divided by the difference between the two extreme values of the measured cumulative displacements, σ_2, and regression coefficient, R. These values describe what is seen visually in in FIG. 5 where σ_1 and σ_2 values from donut test are 0.014 and 0.012 respectively for LVDT and 0.023 and 0.019 for the potentiometer, which explains more scatter in potentiometer output statistically.

In addition to the different hysteretic behavior of the sensors, the magnitudes of the displacements also differ. Considering that average material temperatures are greater around LVDT due to the heat generated by LVDT displacements were normalized by temperature variations in order to compare the sensor outputs. The differences between consecutive sensor readings were divided by the corresponding relative temperature readings when temperature changes were greater than 0.5 ^{o}C. Setting a threshold temperature difference eliminates small, irregular responses of the sensors. According to the results, the potentiometer is less sensitive per unit temperature change than the LVDT for the plastic plate and donut tests. For the plastic tests, the potentiometer measured approximately half the displacements of the LVDT per unit temperature changes.

Transient response

Time histories of responses of potentiometer and eddy current sensors to a dynamic drop ball impacts on the device shown in FIG. 3 are shown in FIG. 6. Spikes represent each impact, with the magnitude of the response being the difference between the top of the spike and the position of the sensor at rest (middle of the thick, noise line).

Dynamic impact displacements measured by high and low tension potentiometers are compared in FIG. 7 to the benchmark LVDT and eddy current sensors. These comparisons were obtained with five pairs of sensors, where each pair responded to the same impact to assess the relative accuracies of the various sensors. There is more scatter in the comparisons of potentiometer and the benchmark sensors than for the comparison of the two benchmark sensors.

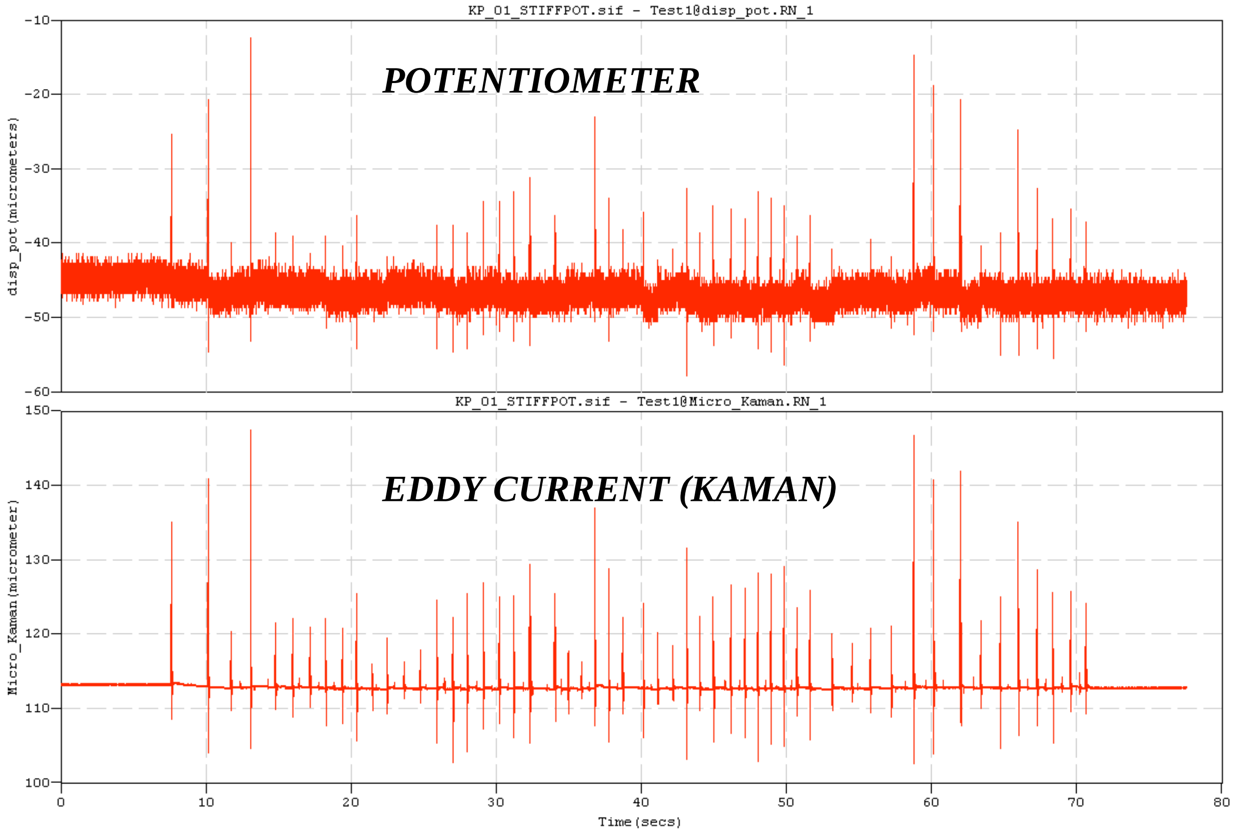

FIG. 6: Comparison of potentiometer and Kaman (eddy current) sensors to dynamic events produced by the same drop weight impacts

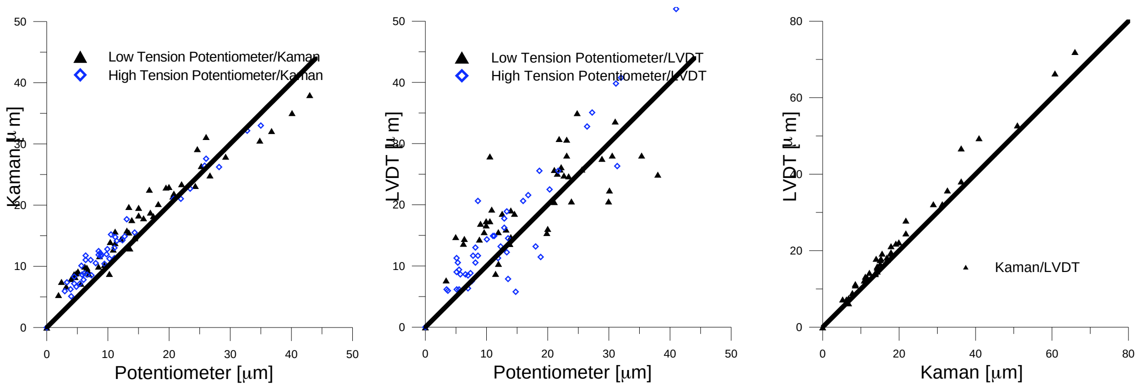

FIG. 7: Comparison of various sensors to the same impact produced by the laboratory device

Detailed time histories from the same drop weight events measured by low-tension potentiometer and the Kaman eddy current sensors are shown in FIG. 8. Displacement waveforms measured by the potentiometer are identical to those measured by the other sensor. It is apparent from all of the other response waveforms (Ozer, 2005) that neither the stiffness of the spring nor the vibrations in the string cable had any significant influence on the response of the potentiometer at the frequency of the input motion. Range of frequencies of dynamic test displacements are 10 to 100 Hz whereas those measured from blast induced ground vibrations are 10 to 30 Hz. This test was repeated with other sensor combinations such as LVDT, with two types of potentiometer, and Kaman-LVDT.

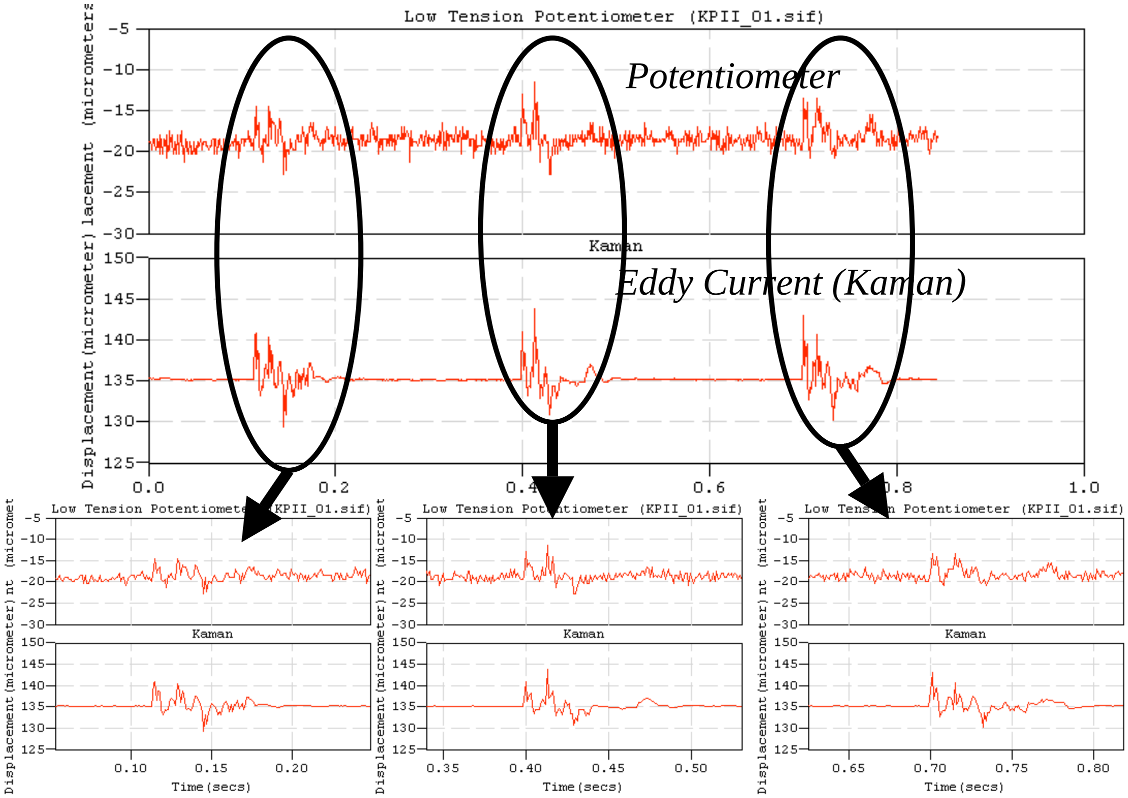

FIG. 8: Responses of low-tension potentiometer and eddy current sensor to the same three impacts

Cables on these sensors have also fundamental frequencies that might amplify their response. Thus vibrations of the string cable could produce additional response if the potentiometer were to measure a very high frequency motion. While such an additional response would be rare, it is possible. The natural frequency of the potentiometer string cable with the current settings in the field and laboratory (length of the fixed cable, tension in the cable etc.) is estimated to be 400 and 600 Hz for low-tension and high-tension potentiometers respectively. Since neither the dynamic test nor the real blast events involve frequencies that high, additional relative motion or vibration in the string cable is unlikely.

In addition to the frequency response effects above discussed, noisy output of the potentiometer might be another source of error that might prevent response to the blast events. Such non-response occurred during field monitoring, while the potentiometers were installed in the test house. Crack displacement induced by those ground motions were not captured by the potentiometers due to the noise which obscured the potentiometer output. The LVDT connected to the same data acquisition system in the house measured the 2-5 μm (79-197 μin) of crack displacements. Noise in the potentiometer output (4-6 μm (150-240 μin) peak-to-peak) was produced by the wired data acquisition system. When deployed with the wireless system, noise level in the potentiometer output measured at a sampling frequency of 10 Hz was around 0.4-0.5 μm (15-20 μin) peak-to-peak.

CONCLUSION

The following summarize the performance of the potentiometers for long-term environmental changes and transient impact loadings:

- Responses to long-term, cyclical changes in displacement are linear.
- Hysteresis is sufficiently small to allow tracking of changes in displacements as small as 0.1 μm (3.94 μin). Hysteretic bandwidth is approximately the same for potentiometer and LVDT in the donut test whereas LVDT hysteretic bandwidth is approximately 50 % smaller in the plate tests.
- Drift is no greater than that of the LVDT or eddy current sensors.
- Response to transient displacements greater than 2 μm (78.7 μin) at frequencies between 10 to 100 Hz in general matches that of eddy current and LVDT sensors.
- Response to transient displacements is less than that of LVDT and eddy current sensors for especially displacements smaller than 15 μm (591 μin). The average ratio of potentiometer displacement to eddy current and LVDT sensors are 0.7 at this range of displacements.
- Response to long-term changes was observed to be less than that of LVDT in the plastic plate and donut tests. The average ratio of potentiometer displacement to LVDT is measured to be 0.4 in the plastic plate test, 0.5 in the donut test, and approximately same in the aluminum plate test.
- Potentiometer output noise is only 0.5 μm (19.7 μin) peak to peak when operated with the wireless system and some 10-15 μm (394-591 μin) peak to peak when operated as a part of the wired system at the same excitation level.

Potentiometer displacement sensors with their very low power consumption, no warm up time and excitation voltage flexibility are suitable for the wireless sensor network. As described by Ozer (2005), the sensorboard of the wireless system provides only 2.5, 3.3 and 5.0 volts of excitation voltage, which eliminates the usage of LVDT and eddy current sensors. As compared to these sensors, power consumption of the potentiometer is considerably smaller and requires no warm up time, which is crucial for wireless sensor nodes relying on just 2 AA batteries. In addition to these gains by using potentiometers with the wireless systems, long-term and transient responses of the potentiometers are reasonably accurate and reliable.

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