Surface-Contacting Vibrometers for Seismic Landmine Detection

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ABSTRACT

A technique has been developed that exploits remote seismic sources and local measurement of the surface displacement of the ground for the detection of buried landmines. Most of the previously reported investigation of this technique has focused on non-contact displacement sensors in order to ensure the safety of the operators of both handheld and vehicle-based systems. This is not inherently a constraint that requires a non-contact sensor, but rather one requiring a sensor that is non-intrusive (i.e. its presence does not alter the measured quantity). Current research is directed toward the development of autonomous and semi-autonomous robotic systems based on this technique. Here both unit cost and power consumption are issues of comparable importance to the survival of the sensor platform. Non-intrusive surface-contacting vibrometers are therefore a reasonable alternative. Several configurations have been studied for suitable vibrometers. The configuration that has shown the most promise is based on a commercial accelerometer coupled to the ground with a small normal force and isolated from the backing structure that is used to reposition it between measurements. It is a relatively simple matter to detect seismic motion with an accelerometer. The major issue in an effective implementation of the technique is to combine reproducibility with fidelity in the measurement. These are competing goals in that reproducibility is easily achieved with large normal forces, but fidelity requires that these be small. Sufficient reproducibility for imaging purposes has been achieved with normal forces that pose no danger of landmine detonation. Unlike reproducibility, fidelity is linked to both the nature of the imposed force and to its magnitude through the nonlinearity of the soil’s elasticity. Both continuous and incremental motions of the sensor platform have been studied, although incremental movement shows the most promise for the intended application.

1. INTRODUCTION

Since 1996, a seismic landmine-detection system has been under investigation at Georgia Tech. The system is well documented in the literature 1,2. It is based on the excitation of audio-frequency seismic surface waves (Rayleigh waves) by a remote source and the measurement of the full wave field with a non-intrusive sensor. The source is an electrodynamic shaker that has been coupled to the ground so as to preferentially excite Rayleigh waves. These interrogate only the near surface layers of soil because they decay exponentially into the medium. Landmine images are constructed by post-processing the measured displacement signals over an array of measurement locations. This has been described in previous papers 1,3. In previous work the array has been constructed synthetically using a small number of sensors. The sensor that has been tested most extensively uses an 8 GHz radar signal to measure the surface motion of the ground 4. Non-contact sensors using ultrasonic signals have also been demonstrated 5. Initial tests revealed that the major issues for a ground-contacting sensor are fidelity and reproducibility. Sensitivity is not a major issue because commercial accelerometers with 10 to 100 mV/g sensitivity offer signal-to-noise ratios that are superior to the non-contact sensors that have been studied over the entire frequency range of interest (50 to 1000 Hz). Accelerometers measure the second derivative of the displacement that was measured by the non-contact sensors, and the crossover point for their signal-to-noise performance with respect to these sensors is well below the lowest frequency in the operating band of the mine-detection system.

In order for a ground-contacting sensor to offer sufficient fidelity to operate in a seismic landmine-detection system similar to the systems that have been tested with non-contact sensors, it must be non-intrusive. This requires that it satisfy three criteria. First and most obviously, it must not impose a static force that is sufficient to detonate a buried pressure-fused landmine. Second, it must not load either the ground or a buried mine to alter the surface motion in a way that diminishes the quality of the resulting
image with respect to the unloaded case. In this respect some alteration of surface motion may be tolerated or even desired since it may enhance the contrast between a mine and the surrounding soil. Finally, the sensor must not scatter the seismic interrogation signal to an extent that it would shadow other elements in an extended array.

Ground-contacting sensor prototypes were tested in a laboratory experimental model that has been described in previous papers. The model is a wedge-shaped tank filled with 50 tons of damp compacted sand, which has been shown to reasonably simulate the properties of a variety of soils.\textsuperscript{6,7,8} Inert landmines were buried in a 1m\textsuperscript{2} area in the center of this tank. The sensors were discretely repositioned in a raster scan over this area using a computer-controlled positioning system. This was similar to the scans performed with non-contact sensors except that the sensor was lifted off the surface after each measurement and replaced at the next measurement point.

2. PRINCIPLES OF OPERATION

Figure 1 depicts a generalized two-degree-of-freedom model for the ground-contacting sensors that are under consideration. The sensor head is modeled as a small mass ($m_1$) that is attached to the ground through a spring ($k_0$) that represents the stiffness part of the ground’s input impedance. Previous experiments have shown that the input impedance of the sand in the model and the soil at various field sites is dominantly stiffness-like in the frequency range of interest for seismic mine detection.\textsuperscript{9} Based on the ratio of drive current, which is proportional to applied force for an electrodynamic shaker, to soil acceleration measured at the source and the ratio of the source’s contact surface area to the surface area of the ground contacting sensors it is possible to approximate $k_0$ as $4 \times 10^6$ N/m. This, of course, neglects the radiation mass and resistance loads that the sand would also impose on the sensor head. The mass component may be considered to be a portion of $M_1$ and the radiation resistance is one of several damping mechanisms that have been neglected in the model. The sensor head is attached to a backing mass that is also modeled by the lumped mass ($m_2$) by means of a second spring ($k_1$). The backing structure is anchored through a third spring ($k_2$) that isolates the backing mass from the supporting structure. In the case of the laboratory experiments this supporting structure is the positioning system. Although the positioner is not rigid it has been used as a reference frame in all of the previous experiments with non-contact sensors. The sensors were designed so that the combination of $k_2$ and $m_2$ was sufficient to isolate the backing mass from motion of the positioner over the frequency range of interest. $k_1$ was selected to isolate $m_2$ and to be small in comparison with $k_0$. $m_1$ was chosen to be as light as practical. The motion of the sensor head in this model is described by a system of equations as follows:

\[
\begin{bmatrix}
  k_0 + k_1 - m_1\omega^2 & -k_1 \\
  -k_1 & k_1 + k_2 - m_2\omega^2
\end{bmatrix}
\begin{bmatrix}
  x_1 \\
  x_2
\end{bmatrix}
= \begin{bmatrix}
  k_0 \cdot x_0 \\
  0
\end{bmatrix}
\] (1)

The first sensor prototype to be tested was designated the \textit{Pogo-Stick} because it was similar in appearance to one of these toys. This sensor is depicted in figure 2. Originally the sensor was constructed without the foam collar, but this was added to permit motion of the sensor head in the horizontal plane and rotations of the head. This was necessary because the ground surface motion associated with a Rayleigh wave is elliptical in nature even though the sensor was only intended to measure its vertical component. The sorbathane\textsuperscript{TM} viscoelastic polymer layer was added to the sensor head to improve the coupling to the sand’s surface. The coil springs used in this sensor had a combined stiffness of $1.3 \times 10^2$ N/m, which was measured using a spring scale. The foam collar was constructed from a polyethylene foam pipe insulator. Its stiffness was measured on an Instron\textsuperscript{TM} model 5569 load frame to be $5.4 \times 10^3$ N/m. The dynamic masses of the rod and sensor head were approximately 40g and 5g respectively. These values, used as input to the model depicted in figure 1, predict a sensor response that is shown in figure 3. The motion $x_1$ is a good replica of the desired motion $x_0$ over the entire frequency range of interest. Here it is apparent that the two modes of the sensor bracket the frequency range of interest. At the low end of
this range is the resonance of the rod (backing mass) against the coil spring. At the high end of this range is the resonance of the sensor head against the ground’s stiffness.

Figure 1: Lumped element model for the response of a ground-contacting vibrometer

Figure 2: Configuration of a *Pogo-Stick* ground-contacting vibrometer
The second sensor type that was tested was free standing. It is shown in figure 4. This sensor was repositioned by lifting and placing it such that it was completely decoupled from the positioning system during the measurement. This sensor is an appealing candidate for a large sensor array because it provides its own biasing force by means of its tail mass. It also has the advantage that it is completely self-contained and is therefore easily waterproofed and easily replaced at any location within an array. The tail mass was selected to be 450g because this was determined to provide more than sufficient biasing force to guarantee reproducibility in the measurements. The foam collar and sensor head were functionally identical to those used in the Pogo-Stick sensor, but $k_3$ was effectively zero during the measurement. These parameters used as input to equation 1 predict the sensor response shown in figure 5. Again the response $x_1$ is a good replica of the desired motion $x_0$ over the entire frequency range on interest. Here the high-frequency resonance is the same as that depicted in figure 3 but the low-frequency range of the sensor’s response has been extended downward by nearly two octaves.

### 3. SENSOR BIASING FORCE

The Pogo-Stick offered an excellent test bed for the examination of the effect of biasing force on the performance of ground-coupled sensors because the force could be easily varied by adjusting the compression of the coil spring using the positioning system in the experimental model. The two-degree-of-freedom model assumed intimate contact between the sensor and the ground. Thus the model was insensitive to the applied biasing force (pre-stress in $k_0$, $k_1$, and $k_2$). Modeling any other contact condition would have required nonlinearity in $k_0$. Nonlinearity in the elastic behavior of the sand in the experimental model has been documented in previous papers\textsuperscript{11}, and both soil and soil-loaded landmine nonlinearity have been studied by other authors\textsuperscript{12,13,14}, but these nonlinearities are not sufficiently well understood for inclusion in the model. Thus an experimental approach was selected to address this issue.
Figure 4: Modular ground-contacting Vibrometer

Figure 5: Predicted response of modular ground-contacting sensor
Figure 6 shows the measured responses from linear scans of the Pogo-Stick sensor over a buried TS-50 antipersonnel (AP) landmine using 4 different biasing forces (1.1, 3.6, 9.2, and 11.4 N). The presence of the mine is apparent in each of these scans. It is clear that the lowest biasing force yields a result that is deficient in point-to-point reproducibility compared to the other measurements. Increasing bias force beyond this results in a loss of fidelity. Both the on- and off-mine responses diminish as the bias force is increased. This is an indication of nonlinearity in both the sand-loaded landmine and in the surrounding sand. The most likely mechanism of this nonlinearity is that the sensor biasing force creates an overburden pressure on the sand surface similar to the lithostatic pressure that causes vertical stratification of material properties by packing sand grains\textsuperscript{12}. This results in a local increase in the shear modulus of the sand and a corresponding decrease in the vertical motion. The spatial extent of the effected region may play a significant role in the mutual scattering that will occur in a physical array. Thus nonlinear effects are likely to impact both the response an individual vibrometer and the sensor interactions in an extended vibrometer array.

Figure 6: Waterfall plots of measured displacements from linear scans over a buried TS-50 AP mine with a Pogo-Stick vibrometer using four different biasing forces.

Figure 7 shows image pixels that were generated from the data depicted in figure 6 using the imaging algorithm that has been previously reported. This algorithm involves the removal of forward propagating waves in k-space followed by temporal windowing of the remaining backward wave-field about the
Each pixel represents the RMS level in that window. It is clear from this figure that all of the measured data was sufficient to image the buried mine with about 20 dB of background contrast. The reproducibility problems associated with small biasing forces diminish the background contrast of the landmine using this algorithm by about 3 dB as compared to the other results. The fidelity problems noticed with the high biasing forces do not have adverse impacts on these images.

Figure 7: Image pixels formed from linear scans over a buried TS-50 AP landmine with various biasing forces.

4. IN-PLANE MOTION

As previously mentioned, the foam collar that was used to isolate the sensing head served a secondary function of providing the vibrometer with a horizontally and rotationally soft suspension. This permitted the sensor to follow the elliptical ground motions associated with Rayleigh waves. Figure 8 shows data collected in an experiment that was performed with a Pogo-Stick sensor fitted with a triaxial accelerometer (PCB model W356CA12). This accelerometer caused $m_1$ to increase from 5g to 20g, and had a larger contact area on the ground that increased $k_0$ to about $1.6 \times 10^7$ N/m. The data shown in 9A, which were collected with a 1.1 N biasing force, clearly show both the prograde motion associated with the first arrival of the leaky surface wave and the retrograde motion associated with the Rayleigh wave. The data shown in 9B were taken with a 6.1 N biasing force. This figure shows that the nonlinear effects, which cause diminished vertical motion, also change the relationship between vertical and horizontal displacements. These changes are most pronounced for the motion associated with the...
Rayleigh wave. This is probably because the shear modulus of the sand is more sensitive to overburden pressure than is the bulk modulus, and the Rayleigh wave is dominantly shear-like.

Figure 8: Motions measured in two orthogonal directions 1.5 m from a seismic source using a Pogo-Stick vibrometer with two different biasing forces: 1.1 N (A) and 6.2 N (B)

5. CONFIRMATION SENSOR

The most promising application for an array of ground-contacting vibrometers is as a confirmation sensor. This is because scanning an individual ground-contacting vibrometer over the ground is an intrinsically slow process, but building a large array of vibrometers can be cost effective (commercially available accelerometers have been identified that place the cost per sensor below $10). Thus a small area of ground can be scanned very quickly. Based on initial measurements, it is reasonable that an area up to several square meters can be examined in approximately one second if mutual-scattering effects can be neglected and a sufficient number of channels are available for data collection. Thus, if a system with fast scanning capability and a high false alarm rate and/or low spatial resolution has identified the location of a probable target, a semi autonomous platform supporting an array of ground-contacting vibrometers can be dispatched to confirm the presence of a landmine and pinpoint its location. Such an array was synthesized using the modular vibrometer depicted in figure 4. Data was collected on a 1m-by-1m square grid in 1 cm steps (i.e. a 10,000 element array was synthesized). A VS-1.6 antitank landmine was buried 5 cm deep in the center of the scan region. For three instants in time the measured wave-field is depicted in figure 9. Here, absolute acceleration is plotted using a 30 dB color scale. In 9A the Rayleigh wave front has just entered the left of the scan region. The landmine is already apparent here because of motion excited by the faster waves, to which the accelerometer is more sensitive than the non-contact displacement sensors that have been used in previous experiments. In 9B the Rayleigh wave is interacting with the buried mine. On the left side of this figure the waves scattered (and converted into Rayleigh waves) from the fast waves’ landmine interactions can be seen. In 9C the Rayleigh wave has propagated beyond the mine location and the scattered wave-field is clearly apparent.
Data collected in the experiment was processed using the same algorithms as the data depicted in figure 7. The resulting two-dimensional image is shown in figure 10. The image shows the mine with approximately 30 dB of background contrast. There is clutter in the image that is higher than –30 dB, however this is clearly linked to the presence of the mine (the clutter forms an arc centered on the mine location). This is related to the scattering and mode conversion of faster waves by the buried mine to which the accelerometer was found to be unusually sensitive. It should be possible to modify the imaging algorithm to eliminate this clutter and possibly to use the information that gave rise to it to enhance the background contrast.

6. CONCLUSIONS

Ground-contacting sensors show great promise for incorporation into arrays that can be used as confirmation sensors. Initial testing has identified reproducibility and fidelity as the major issues in implementing such an array. Using synthetic array techniques, which neglect sensor coupling within an
array, two ground-contacting vibrometer designs were found to be sufficient for imaging buried AT and AP mines with high background contrast using minimum biasing forces of between 1 and 4 N.

Figure 10: Image of a buried VS-1.6 AT mine formed with data collected in a two-dimensional scan of a modular ground contacting vibrometer.

6. ACKNOWLEDGEMENTS

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7. REFERENCES


