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Imaging of Acoustic Waves in Sand

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1. ABSTRACT

There is considerable interest in detecting objects such as landmines shallowly buried in loose earth or sand. Various techniques involving microwave, acoustic, thermal and magnetic sensors have been used to detect such objects. Acoustic and microwave sensors have shown promise, especially if used together. In most cases, the sensor package is scanned over an area to eventually build up an image or map of anomalies. We are proposing an alternate, acoustic method that directly provides an image of acoustic waves in sand or soil, and their interaction with buried objects.

The INEEL Laser Ultrasonic Camera utilizes dynamic holography within photorefractive recording materials. This permits one to image and demodulate acoustic waves on surfaces in real time, without scanning. A video image is produced where intensity is directly and linearly proportional to surface motion. Both specular and diffusely reflecting surfaces can be accommodated and surface motion as small as 0.1 nm can be quantitatively detected.

This system was used to directly image acoustic surface waves in sand as well as in solid objects. Waves at frequencies of 16 kHz were generated using modified acoustic speakers. These waves were directed through sand toward partially buried objects. The sand container was not on a vibration isolation table, but sat on the lab floor. Interaction of wavefronts with buried objects showed reflection, diffraction and interference effects that could provide clues to location and characteristics of buried objects. Although results are preliminary, success in this effort suggests that this method could be applied to detection of buried landmines or other near-surface items such as pipes and tanks.

2. THE PROBLEM

Various applications require detection and sometimes identification of objects buried in soil, although not necessarily to any great depth. A variety of methods for detecting such objects have been explored, including ground penetrating radar/microwave imaging and interferometric techniques, acoustic methods, magnetic or electrical impedance measurements, chemical (explosives) detection, x-ray, neutron capture, nuclear resonance measurements, animals trained to detect odors, and thermal imaging. Each of these methods has shown promise, at least under some conditions of soil type, moisture content, depth or plant cover, but none has been accepted as the ideal technique. Research on these techniques continues, as does research on new approaches and on data fusion from multiple sensors.

3. BRIEF REVIEW OF OTHER MINE DETECTION EFFORTS

During April 24-28, 2000, the SPIE sponsored a meeting titled “Detection and Remediation Technologies for Mines and Minelike Targets V” in Orlando Florida. Nearly 300 papers on a variety of detection and data interpretation techniques, as well as other landmine related concerns were presented. These were published as SPIE Proceedings, Volume 4038, parts 1 and 2[1] and provide both a valuable reference and evidence of the extensive interest in this serious humanitarian and combat problem. Another broad overview of numerous possible techniques is contained in a report by McDonald, et al[2] and published by the Rand Corp.

Among notable efforts leading to images of buried objects, were several using scanned radar, acoustic or radar combined with acoustic detection methods. In the SPIE Conference cited earlier, Sabatier and Hickey[3] (p 633) modeled the transfer function for sound waves in earth. Xiang and Sabatier[4] p. 645 used arrays of geophones placed on the ground and scanned laser Doppler velocimetry (LDV) measurements to map the response of buried objects to sound as well as the effective attenuation of sound in soil. Various soil compositions and ground covers were tested and considerable variation in attenuation and signal to noise ratio were noted. The size and depth of the mine also affected detectability using these methods. Rosen, et al[5] also tested Laser Doppler Velocimetry (LDV) on buried mines, and concluded the approach was promising. Their best success rate was with high spatial resolution imaging. Scott, et al[6] used elastic waves to interact with buried mines and a scanning electromagnetic radar system to detect these disturbances. Acoustic frequencies of 100 to 1000 Hz were used, depending on the depth of burial. The researchers state that resonances in the mine and associated mechanical components provide the primary cues for detection. Items for further study were field tests and the effect of clutter and ground cover on the success rate. Schröder and Scott[7] modeled the interaction of elastic waves with various buried objects and produced computed images of the scattered waveforms. Similar images were obtained by the INEEL imaging technique described below as well as by various scanning methods used by others. Lee and Scott[8] modeled near field elastic waves produced by a beam forming array and their interaction with objects. Lafleur, Sabatier and Alberts[9] used scanned LDV to identify the shapes of buried objects as a means of improving the success rate for detection of mines. Success was claimed and agreement with predicted wave shapes was shown.

These earlier studies provide evidence that acoustic/elastic wave techniques are a promising approach to locating and identifying the presence of landmines. Based on this assumption, this paper describes the use of a new imaging methodology, the INEEL Laser Ultrasonic Camera, for providing fast, nonscanned imaging of elastic waves on the surface of the ground that could be extended to subsurface object detection.

4. THE INEEL LASER ULTRASONIC CAMERA

This system (figure 1) has been developed for directly imaging surface vibrations due to resonances or to elastic waves traveling through a material. A laser beam is divided into object and reference beams. The object beam reflects from the vibrating object and is phase modulated at the vibration frequency, f, at each point on the surface. The reflected light is collected and imaged into the photorefractive material (PRM). Simultaneously, the reference beam, having been separately phase modulated at a frequency $f + \delta f_{ref}$, illuminates the PRM. Dynamic holographic recording with fringes moving at a rate dependent on δf_{ref} occurs and the resulting image is reconstructed through 2 wave or 4 wave mixing processes. The diffraction efficiency of this process at each point of the image hologram is directly proportional to the amplitude of the vibration at the corresponding point on the object. Thus, the intensity of the reconstructed holographic

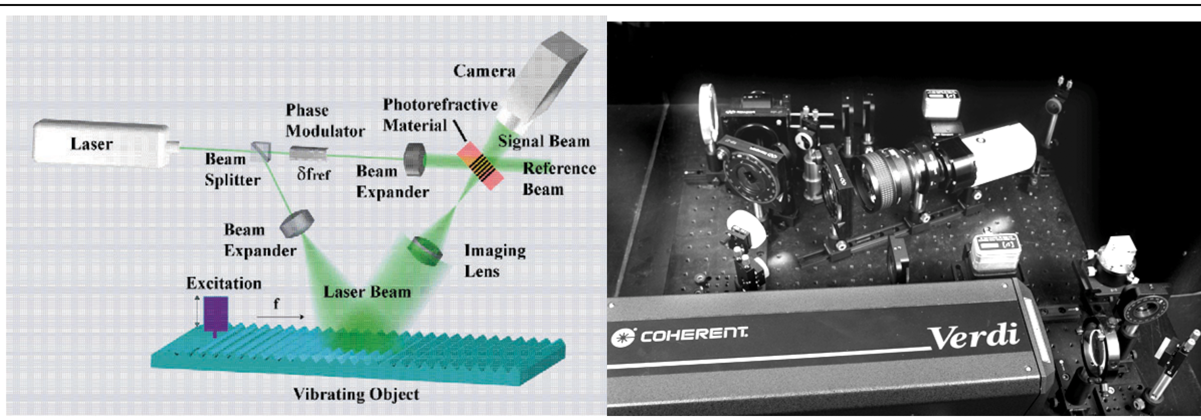

Figure 1: INEEL Laser Ultrasonic Camera

image is proportional to the original vibration amplitude. The imaging optics determine the size of the imaged area, and often consist of camera lenses. A typical stand off distance (from subject to imaging lens) is 1 meter for the bench top prototypes.

Resonance, reflection, diffraction and interference of elastic waves and their interactions with the geometry, defects, and material properties of an object are easily viewed. Both amplitude and phase information is recorded at each pixel of a video camera, and read-out is at normal frame rates. Unlike conventional passive imaging interferometric techniques, interference demodulation occurs through dynamic holography within a photorefractive material (PRM). This eliminates the need for fringe analysis and external optical path stabilization. The technique utilizes narrow band acoustic frequencies that are tunable over a very wide range (Hz to GHz). By use of heterodyne techniques (i.e. $\delta f_{ref} < f_{PRM}$), acoustic motion at any frequency is down mixed to match the frequency response f_{PRM} of the PRM. For Bismuth Silicon Oxide (BSO), $f_{PRM} \sim 50$ Hz, while for Gallium Arsenide (GaAs), the response is about 1 kHz. No special sample surface preparation is needed, and acoustic motion from both specular and diffusely reflecting surfaces can be imaged.

4.1. Applications

The system has been used to visualize and to quantitatively measure 40 kHz traveling anti-symmetric waves in sheet materials[10] (figure 2); bulk waves in thick aluminum[11] (figure 3), plate resonances (figure 4) and motion of MEMS devices such as resonant acoustic filters for communications devices and micromirrors[12] (figure 5). Most recently, we have applied the technique to detection of objects buried near the surface of the earth. Acoustic surface waves tend to interact with buried objects that are on the order of one wavelength deep. For 16 kHz waves in sand, this is approximately 2 cm. Deeper penetration is possible with lower frequencies. In all cases, the waves were directly imaged at video frame rates, without scanning, with 0.1 nm resolution of vibrational amplitude and with no or minimal post processing.

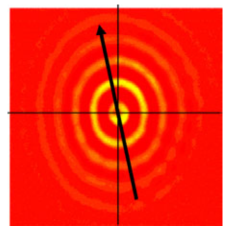

Figure 2: Acoustic waves traveling out from a central point in copy paper. Note anisotropic wave speed. In all cases, intensity is proportional to vibration amplitude

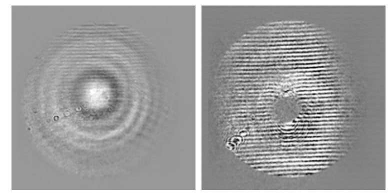

Figure 3: (left) waves reflected and diffracted by shallow flat bottomed hole on bottom of a thick aluminum block (seen from top). (Right) waves diffracting around the hole, seen from the bottom.

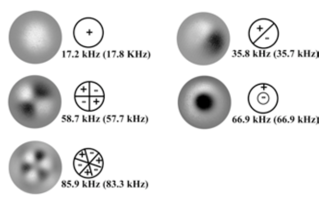

Figure 4: imaged and computed resonances of a clamped circular plate

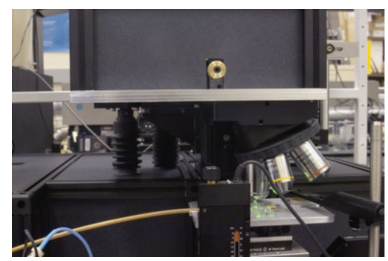

Figure 5: GHz Acoustic Microscope

4.2. Technology:

The INEEL ultrasonic camera utilizes dynamic heterodyne holographic interferometry recorded in photorefractive materials to demodulate and display the vibration image data. Since the method is holographic, the 2-wave or 4-wave reconstructed data consists of a full field image recordable by a video or other camera (it can even be directly viewed by the eye). The image intensity at each pixel has been shown[13] to be proportional to the product of the J_0 and J_1 Bessel functions of the first kind. For most acoustic applications, this results in linear response to the vibrational amplitude for each pixel at the corresponding point on the object and at the excitation frequency. Furthermore, it is quite simple to calibrate each data set for this proportionality, including such variables as variations in specimen reflectivity, spatial variations in beam intensity, etc. This calibration is directly referenced to the wavelength of the laser. Spatial and amplitude resolution is dependent on the pixel count and bit depth, respectively, of the video digitizer, as well as the signal to noise level.

5. THE INEEL APPROACH

The purpose of this research was to demonstrate that the INEEL Laser Ultrasonic Camera could be used to directly image acoustic waves in sand and their interaction with buried objects (figure 6). We were encouraged by others' success in using acoustic/elastic waves to detect and locate buried objects, including mines in soil.

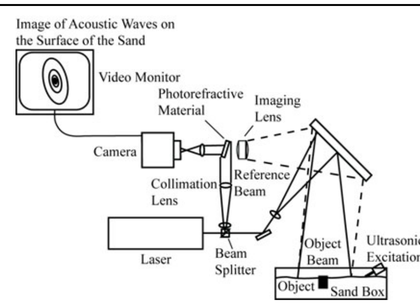

Figure 6: The INEEL Ultrasonic Camera applied to measurements on sand

Applying the INEEL acoustic imaging technique to the detection of objects in soil involves a number of problems. Foremost among these is that of discriminating nanometer scale vibrations from general environmental motions that are potentially much larger. The goal was to image acoustic waves in sand or soil without vibration isolation. Another limitation involved the illumination of a significant area of sand with sufficient intensity to allow one to image the acoustic waves. This involved such factors as laser power, soil reflectivity and reflected light gathering efficiency. Initially, a region 46 cm across was illuminated by 1 watt of total power at 532 nm from a Coherent Verdi^{tm} laser. Ultimately, only the central 20 cm proved useful due to the acoustic attenuation properties of sand.

The excitation and propagation of acoustic waves in such loose granular materials also required considerable effort for success. While we have just begun this study, we have demonstrated that this type of interferometric measurement of nanometer amplitude vibrations can be done without a vibration isolation table. Furthermore, we have shown that we can directly image waves traveling in dry sand, as well as waves interacting with objects inserted in the sand.

6. EXPERIMENTAL ARRANGEMENT

Test Bed: bags of common construction sand were emptied into a large polyethylene container sitting on a vinyl tiled concrete lab floor (figure 7). No specific vibration isolation was used. The sand was dampened, lightly packed and then allowed to dry. A 150 mm diameter mirror on an optical table directed the illumination beam down onto the sand, and collected the reflected light for processing by the INEEL acoustic camera, also on the table. The distance from the mirror to the sand was about 1 meter.

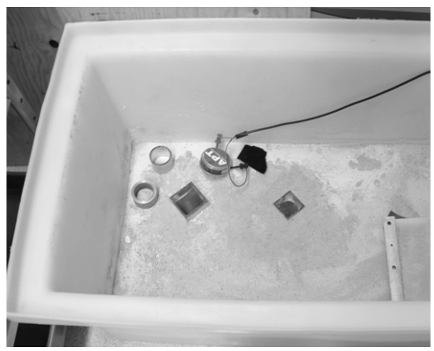

Figure 7: Polyethylene tub with sand, speaker and buried objects

Figure 8: Acoustic speaker used for excitation of elastic waves in sand. Cone is shown by arrow.

Excitation: a variety of excitation methods were tried, but the best source proved to be a small acoustic speaker manufactured by APT (figure 8) that could be partially buried in the sand. The most successful excitation was obtained by partially burying an 8-ohm, 50 watt, APT-50 Super Tweeter directly in the sand. The plastic horn was removed and the metal cone was buried to a depth of 1 cm at an angle of 45 degrees with respect to the sand surface. This speaker was driven by a sinewave generator operating at 16Khz and a power amplifier with an output of around 10 watts, which produced an elastic wave train directed toward the surface in the sand.) This frequency (16 kHz) was selected, despite rapid attenuation in sand, because it provided a number of wave fronts within the field of view. Lower frequencies might be more suitable in real world situations due to improved depth of detection or lower attenuation in sand or soil.

Method: initially, a 46 cm diameter area was illuminated with about 1 watt of 532 nm laser light, (0.6 mW/cm^2, or 6 W/M^2). This area proved to be larger than the effective range of the acoustic waves at our frequency and detection level, so the region illuminated and imaged was reduced to about 20 cm. An SMD (now Dalsa) 1M15 scientific digital camera utilizing a CCD array of 1M pixels at 12 bits was used to capture images of the elastic waves. The camera was externally controlled using a proprietary software package from SMD and was operated at 4 frames/second with 512x512 pixels (2X binning).

A Labview virtual instrument (VI) was written to phase lock the camera to the acoustic excitation so that image averaging and subtraction could be performed. Much of the floor vibration was automatically accommodated by the adaptive nature of the photorefractive process used for interference demodulation. However, not all of the environmental vibration was eliminated thereby requiring averaging over multiple images to extract the desired vibration data with acceptable signal to noise ratio. Image acquisition was accomplished by acquiring 320 phase locked frames over a period of 80 seconds and storing them for post processing. A macro written in Media Cybernetics Image Pro™ was used to separate the images by phase/frame orientation. Another macro was written to perform nonweighted averaging as well as subtraction on the 320 frame acquisitions. This produced a final set of two image frames that had a phase relationship of 0 and 90 degrees, relative to the acoustic excitation. This post processing scheme improved the signal to noise ratio to the point that we were able to overcome the environmental noise introduced by decoupling the region of interest from the isolated optical table. Use of a faster photorefractive material (such as GaAs) with otherwise similar gain properties instead of BSO would improve the rejection of environmental vibration noise and reduce the need for this averaging step.

7.RESULTS

Initial tests involved imaging waves in sand alone, see figure 9. These waves attenuated quickly, and became undetectable after 10 to 20 cm. A length of Aluminum hollow pipe of square cross section with 7.5 cm sides was then inserted in the sand to simulate a buried object. The top of the pipe was left above the surface of the sand to aid in visualizing the wave interaction with the pipe. In figure 10, we see the incident acoustic waves striking the pipe, reflecting and then interfering with the incident wave fronts. The geometry of the pipe will strongly affect the nature of the reflection and diffraction of the incident waves. The flat sides of the square pipe were particularly good for clearly showing the reflection of the acoustic wave.

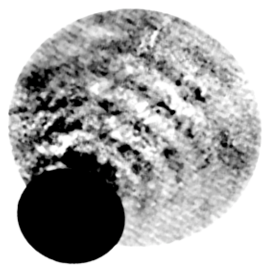

Figure 9: 16 kHz elastic waves traveling outward from the source (black dot) along the surface in sand

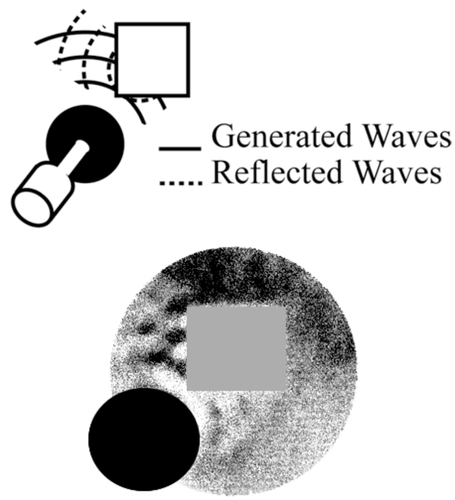

Figure 10: Elastic waves interacting with a square Aluminum pipe standing within the sand.

The quality of these vibrational images is poor due to low signal-to-noise ratio, the granular character of the sand and laser speckle effects. While amplitude calibration data were not recorded, the amplitudes of these waves are estimated to be < 1 nm. It is remarkable that these types of measurements are possible in an environment where one can feel the background vibrations with one's feet. Preliminary work with faster PRMs such as GaAs, as well as theoretical models of the process, give us confidence we can greatly reduce the effects of this background noise on our data. However, this would require re-building our system using IR lasers and optics, as well as substituting GaAs for BSO. This would be necessary for any truly fieldable device.

8. FURTHER WORK

Future work will focus on improved suppression of the effects of environmental noise and on increasing data acquisition rates. More realistic test subjects shall be investigated and the effects of various soil conditions shall be evaluated.

9. CONCLUSION

The INEEL system was successfully used to record images of surface waves interacting with buried obstacles in dry construction sand without scanning or vibration isolation. Wet sand should work equally well, other than possible impact on the acoustic propagation parameters. Waves with frequencies of 16 kHz and wavelengths of approximately 2 cm were imaged up to 20 cm from the source. Lower frequencies are probably better for penetration and may have reduced attenuation, so further efforts will attempt imaging at lower frequencies. In general, photorefractive materials with faster time constants, such as GaAs, provide better suppression of low frequency environmental noise than does the BSO used in these experiments. Furthermore, GaAs operates in the near IR, and laser power at 1.06 microns is cheaper (both in cost and energy requirements) than in the visible, so larger areas could be illuminated for the same cost.

While this preliminary effort was limited in scope, it has shown the promise of using full field imaging techniques for the detection of buried objects, such as landmines. Noncontacting excitation of the elastic waves would also be advantageous, and various authors have explored this avenue (laser excitation: McKnight, et al[14] p. 734; air coupled acoustic/elastic excitation: Sabatier and Hickey[3], p 633)

10. Acknowledgements

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