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3pPAb4. Acoustic response of a buried landmine with a low grazing-angle source array, focused on the ground
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An array of 16 loudspeakers, deployed along a segment of the base of a right circular cone, was used to focus intense tone bursts at low audio frequencies on a soil, with and without a buried target, having a compliant lid. The response of the target site was examined as a function of source frequency, intensity level, and excitation signal type, including multi-tone radiations. Nonlinear interaction to produce sum and difference frequencies at the target site was examined and compared with observations of Korman and Sabatier [J. Acoust. Soc. Am. 116, 3354 (2004)]. [Work supported by the ARL:UT McKinney Fellowship in Acoustics.]

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1. INTRODUCTION

The ongoing international issue of humanitarian de-mining and the need for landmine clearance of farmland and habitable areas is well documented, and many remote detection schemes have been proposed and researched. One technique that has shown promise involves acoustic-seismic coupling to excite compliant and resonant vibration of a buried mine and the soil above it, which can then be detected by optical means such as laser-Doppler vibrometry.\(^1\) Nonlinear vibrations in the mine and soil\(^2\)\(^3\) are of particular interest, as they can be excited at frequencies other than the primary excitation frequencies, and thus can be more easily contrasted with the response of mine-free ground. These nonlinear phenomena occur primarily as a result of interaction at the interface between mine lid and soil.

We present two main innovations that continue work first presented by Barlett et al.\(^4\): the use of a stand-off speaker array for directional ground insonification, and the use of short tone bursts instead of continuous-wave (CW) excitation. The speaker array should allow for amplitudes high enough to create nonlinearity while not requiring transducers to be placed directly above the buried mine. The use of tone bursts is advantageous in that it reduces stress to the speakers and is considerably less annoying to the operator and bystanders. Primary goals of the work presented here were to characterize the radiation field of the array and reproduce the nonlinear phenomena observed by Donskoy\(^2\) and Korman and Sabatier\(^3\) using their method of two-tone excitations combined with our innovations.

2. EXPERIMENTAL METHOD

2.1 Apparatus and Instrumentation

The acoustic source consists of sixteen speakers arranged on a circular arc of radius 6 feet (1.83 m), with the speakers placed every 8 inches (20.3 cm) horizontally (see Figure 1). This configuration creates peak intensity on its center axis, along which every point is equidistant from every speaker. The speakers are wired as two interwoven “modules”, so that the odd and even speakers may be driven independently, thereby reducing the possibility of nonlinear interaction in the speakers. Each speaker module was driven by a 2.8 kW amplifier, although the measurements were done with a fraction of this power. The input signals were generated by digital function generators, which were simultaneously triggered by a TTL pulse from a third function generator.

![Figure 1. Sixteen-speaker array used for ground insonification. The radius of the array is 6 feet (1.83 m), and each speaker is horizontally separated from its neighbors by 8 inches (20.3 cm).](image)

Sound pressure level measurements were taken with a ¼ inch diameter condenser microphone positioned on the ground near the mine casing. The velocity of the mine lid was measured using a geophone glued to its inner surface,
and the ground surface velocity was measured with an identical geophone placed on the ground. The signals from
the microphone and both geophones were recorded on a laptop computer. The mine case itself is a simulant of an
Italian VS-1.6 antitank mine. The measurement setup is pictured in Figure 2. The mine location was at a slant
range of 2.7 m from the center of the array and a grazing angle of 42.5 degrees to the horizontal.

![Figure 2](image_url)

**FIGURE 2.** (a) Example of measurement setup, showing microphone for pressure measurement, geophone for topsoil velocity
measurement, and BNC cable going to the geophone inside the buried mine lid. The white dotted circle shows where the mine is
buried. (b) Geophone glued inside mine lid. (c) Unburied mine.

### 2.2 System Measurements and Procedures

In preparation for present as well as further studies involving off-axis and distant placement of the mine to be
detected, measurements of the array’s beam pattern and axial propagation were made. Examples of these theoretical
and measured curves can be seen in Figure 3.

![Figure 3](image_url)

**FIGURE 3.** Linear field measurements for the speaker array at 250 Hz: (a) beam pattern on ground at distance 10 m, and
(b) axial propagation curve.
It is important to know the resonance frequency of the compliant mine lid, which has been examined in detail. This frequency was determined simply by tapping the lid and observing the frequency spectrum of the impulse response. When the mine was buried, the thump of a hand on the ground proved an effective means of obtaining the impulse response of the mine-soil system. An example of this is shown in Figure 4.

Prior measurements demonstrating nonlinear acoustic mine detection were done with continuous tones of different frequencies within the resonant band of the target. In the present work, the mine was also excited at various pairs of frequencies whose choice was governed by the natural frequency of the mine lid for its burial conditions. The first set of measurements was carried out using continuous waves. Several sets of frequencies were chosen: for the unburied mine, 200 Hz and 220 Hz (around the mine lid’s unloaded natural frequency of 210 Hz), then for a burial depth of 2 cm, 150 Hz and 180 Hz (around the lid’s loaded natural frequency of ~165 Hz). When the mine was buried under 8 cm of soil, another frequency pair of 75 Hz and 125 Hz was used to correspond to the new loaded natural frequency of 100 Hz.

Each measurement was carried out with the mine buried at depths of 2 cm and 8 cm under two varieties of soil (clay and sand). The burial site was located 2 meters in front of the array, on the symmetry axis. Measurements of the soil velocity with no mine present and the lid velocity when unburied were also performed. The typical sound pressure level just above the ground where the mine was buried was 115 dB re 20 μPa.

3. EXPERIMENTAL RESULTS

3.1 Continuous Wave Excitation

Second-order nonlinearities give rise to the well-known features of harmonics, and of sum and difference frequencies when primary waves with two or more frequencies interact. We took the presence of a sum frequency in mine and soil response to be the chief indicator of nonlinearity, the desired detection result. Second harmonics (always generated in power amplifiers, etc.) were judged poor indicators, as these were present in the microphone signal, indicating that they arose in the amplifier-speaker system rather than as a result of mine-soil interaction, and difference frequencies proved difficult to distinguish due to low-frequency noise. As a baseline, measurements were taken on soil with no mine present and the lid velocity when unburied were also performed. The typical sound pressure level just above the ground where the mine was buried was 115 dB re 20 μPa.

FIGURE 4. Example of using impulse response (a) to obtain natural frequency (b) of lid/soil system. The pictured response is for the lid buried under 8 cm of sand. The center frequency in this case is 105 Hz, and the width at 3 dB down is 63 Hz.
FIGURE 5. System second harmonics and other frequencies when excited by continuous waves at approximately 200 and 220 Hz in the absence of mine-soil contact. (a) Acoustic pressure (microphone measurement). (b) Ground velocity on sand with no mine buried. (c) Lid velocity with no soil covering.

Overall, sum frequencies were more commonly observed when the mine was buried in sand as opposed to soil. On one occasion the mine was left buried in 2 cm of soil for two days, and when measurements were taken again, a sum frequency was observed. Increasing the depth of burial to 8 cm caused the sum frequency to greatly diminish and disappear in most cases. Despite the addition of frequencies that more closely matched the new loaded resonance, the only clear sum frequency we observed in 8 cm cases occurred in sand with a higher pair of frequencies. Results for each combination soil type, depth and frequency pair that has been tested are shown in Table 1. Figure 6 shows some examples of the lid velocity spectra for the trials in Table 1.
TABLE 1. Results of bifrequency continuous wave tests for mine buried in soil. “Sum Frequency” column lists the amplitude of the peak in the lid velocity spectrum at the sum frequency in dB down from the primary peaks.

<table>
<thead>
<tr>
<th>Covering Type</th>
<th>Depth</th>
<th>Primary Frequencies</th>
<th>Sum Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil (fresh)</td>
<td>2 cm</td>
<td>200 Hz / 220 Hz</td>
<td>N/A</td>
</tr>
<tr>
<td></td>
<td></td>
<td>150 Hz / 180 Hz</td>
<td>N/A</td>
</tr>
<tr>
<td></td>
<td></td>
<td>200 Hz / 220 Hz</td>
<td>N/A</td>
</tr>
<tr>
<td></td>
<td>8 cm</td>
<td>150 Hz / 180 Hz</td>
<td>N/A</td>
</tr>
<tr>
<td></td>
<td></td>
<td>75 Hz / 125 Hz</td>
<td>N/A</td>
</tr>
<tr>
<td>Soil (settled)</td>
<td>2 cm</td>
<td>200 Hz / 220 Hz</td>
<td>-49.4 dB</td>
</tr>
<tr>
<td></td>
<td></td>
<td>150 Hz / 180 Hz</td>
<td>-47.6 dB</td>
</tr>
<tr>
<td>Soil (dehydrated)</td>
<td>2 cm</td>
<td>200 Hz / 220 Hz</td>
<td>N/A</td>
</tr>
<tr>
<td></td>
<td></td>
<td>150 Hz / 180 Hz</td>
<td>N/A</td>
</tr>
<tr>
<td>Sand</td>
<td>2 cm</td>
<td>200 Hz / 220 Hz</td>
<td>-53.4 dB</td>
</tr>
<tr>
<td></td>
<td></td>
<td>150 Hz / 180 Hz</td>
<td>-44.0 dB</td>
</tr>
<tr>
<td></td>
<td>8 cm</td>
<td>200 Hz / 220 Hz</td>
<td>-47.5 dB</td>
</tr>
<tr>
<td></td>
<td></td>
<td>150 Hz / 180 Hz</td>
<td>-52.8 dB</td>
</tr>
<tr>
<td></td>
<td></td>
<td>75 Hz / 125 Hz</td>
<td>N/A</td>
</tr>
</tbody>
</table>

FIGURE 6. Frequency spectra of buried mine lid velocity, showing clear examples of sum frequencies generated with continuous wave excitation. Here, 60 Hz noise and its second harmonic are often present as well. Plots (a) and (b), for the mine buried under 2 cm of sand, show sum frequencies for primary frequencies both near and away from the loaded natural frequency of the mine. Plot (c) shows a smaller sum frequency peak when the mine is buried under 8 cm of sand. Plot (d) shows how the sum frequency amplitude is also reduced for burial beneath 8 cm of clay soil as opposed to sand.
3.2 Pulsed Excitation

In addition to continuous waves, we excited the mine with short tone bursts. However, the broader nature of the frequency spectrum of a short burst, and thus less energy available near the resonance frequency of the mine, made it difficult to observe sum frequencies. The best results were obtained when relatively long bursts (~20 cycles) were used, as shown in Figure 7.

![Frequency spectrum for lid velocity: 2 cm sand, 20 cycle bifrequency tone burst.](image)

**FIGURE 7.** Frequency spectrum for lid velocity: 2 cm sand, 20 cycle bifrequency tone burst.

4. DISCUSSION AND CONCLUSION

We have succeeded in reproducing nonlinear behavior in a mine/soil system, as first reported by Donskoy\(^2\) and by Korman and Sabatier\(^3\), using different methods. The detection of a sum frequency component, from the nonlinear interaction in the soil-minecase lid system was achieved. The earlier work cited was done with much higher source levels, at positions directly above the target, while we were able to detect sum frequency nonlinearity at a slant range of 2.7 m, and a grazing angle to the horizontal of 42.5 degrees, at a level of insonification on the ground of only 115 dB re 20 µPa. The present approach has the potential for long range stand-off detection at safe distances, which could be enhanced by higher insonification levels and the utilization of tailored signal types and signal processing.

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REFERENCES