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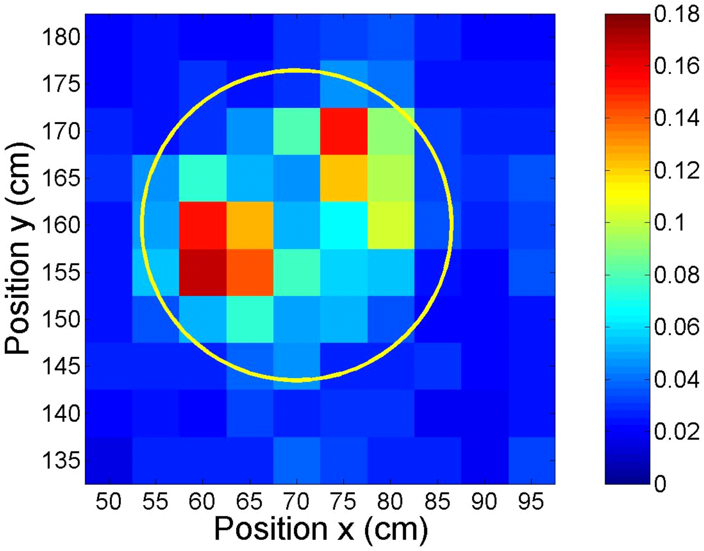

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Report title

Detection of buried land mines with laser vibrometry

Abstract (not more than 200 words)

We have demonstrated that buried land mines can be detected by measuring acoustically induced surface vibrations with a coherent laser radar. The detection methods works well for anti-tank (AT) mines. Two AT mines were used as test objects giving clear resonances around 100 Hz. The objects used to simulate anti-personnel (AP) mines did not show any clear resonances, unfortunately, no real AP mines were tested. No resonances were observed for a stone that was used as a decoy. An important advantage with this method is the ability to perform remote detection of buried mines, both metal and plastic.

Furthermore, we have shown that it is possible to keep the sensitive and expensive parts of the laser radar system far apart from the measurement head. By passing the local oscillator arm in the same fibre cable as feeding the measurement head, the system became fairly insensitive to both movements of the fibre cable and high sound pressure levels on the cable.

Suggested future work includes outdoor field trials to investigate the performance in various types of soil and varied water content. Also, the ability to detect AP mines should be investigated.

Keywords

mine detection, laser vibrometry, coherent laser radar

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Rapportens titel (i översättning)

Detektion av nedgrävda landminor med laservibrometri

Sammanfattning (högst 200 ord)

Vi har visat att nedgrävda landminor kan detekteras genom att mäta akustiskt inducerade ytvibrationer med en laservibrometer. Detektionsmetoden fungerar bra för stridsvagnsminor. Två stridsvagnsminor användes som testobjekt och gav tydliga resonanser omkring 100 Hz. De objekt som användes för att simulera truppminor uppvisade ej några tydliga resonanser, och tyvärr testades inte några riktiga personminor i detta försök. Inga resonanser observerades för en sten som användes som skenmål. En viktig fördel med denna metod är möjligheten att detektera nedgrävda minor, både innehållande metall och metallfria.

Vidare har vi visat att det är möjligt att hålla känsliga och dyrbara delar av laserradarsystemet långt ifrån själva mäthuvudet. Genom att låta lokaloscillatorn gå genom samma fiberkabel som signalen från mäthuvudet blev mätsystemet relativt okänsligt för rörelser i fiberkabeln och det höga ljudtrycket på kabeln.

Förslag till fortsatt verksamhet omfattar fältförsök för att undersöka prestanda i olika jordarter och med olika fuktighet. Även möjligheten att detektera truppminor bör studeras.

Nyckelord

mindetektion, laservibrometri, koherent laserradar

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Contents

Cover: Laser vibrometry image of a low-metal content AT mine buried 6 cm below the surface.

1. Introduction

Detection and identification of buried land mines are important issues, both in wartime and in post-war operations. Several sensors for mine detection have been developed through out the years, such as metal detectors, ground penetrating radar [1] and infra-red (IR) imaging [2, 3]. All the methods have some disadvantages. The metal detectors can only detect mines containing metal. Furthermore, the metal detectors have difficulties to discriminate between mines and other buried metal objects, resulting in a high false alarm rate. Low metal content mines can also be a problem for a ground penetrating radar (GPR).As long as the dielectric characteristics of the mine and the surrounding media are sufficiently different, the GPR is able to detect non-metallic materials. Small objects may be difficult to resolve with radar methods due to the relatively long microwave wavelength. The IR imaging method normally needs pictures from several time instances separated by hours, or alternatively, needs good IR modelling of the investigated area if only one image is used. Therefore, it can be quite a slow method. On the other hand the area coverage capacity with an airborne IR-sensor may be quite high. Our approach of detecting buried land is based on laser measurements of acoustically induced ground vibration. The method has the potentials to be able to detect metal-free mines. Furthermore, the method can resolve both small and large buried objects due to the short wavelength of laser light and small field of view of the receiver. Hence, it is well suited for classification and identification of the mines, based on high spatial and spectral resolution.

When acoustic waves are impinging onto the ground surface, seismic motions in the ground are excited. Slow speed vibrational waves are penetrating downwards into the ground and along the surface. These so called Biot waves are strongly attenuated with a penetration depth of a couple of decimetres [4, 5]. When inhomogeneities are present in the ground, such as buried objects or stones, the vibrational waves are scattered and reflected by the objects and coupled to the vibrational modes of the objects. Already in the 1980s this phenomenon was investigated to detect buried mines using geophones to measure the vibrations. However, it is not particularly practical to use sensors that are in direct contact with the ground when dealing with mines. Therefore, laser vibrometry could be a useful technique to measure the vibration. A laser vibrometer is a non-contact sensor, which is based on coherent laser radar (CLR) techniques. A moving object imposes a frequency shift, a Doppler shift, in an illuminating laser beam. By comparing the frequency shift of the return with the original illuminating laser beam, it is possible to determine the radial velocity of the object. Similarly, a vibrating surface gives a micro-Doppler shift that can be measured by a laser vibrometer. The schematics of a mine detection set-up are shown in Figure 1. From measurements, it is possible to calculate the spectrum of a vibrating surface. Laser vibrometers are relatively common in industrial application, e.g. to analyse vibrations in machinery, cars and mobile phones [6, 7].

Recently several groups have successfully been able to detect mines with the CLR technique [4, 8]. To our knowledge, only commercial equipments from Polytec [6] and MetroLaser [7] have been used to measure the ground vibration with this technique. One disadvantage with these equipments is that the measurement head, which need to be close to the investigated surface, is quite complex and expensive. In this report, we present a fiber-based CLR where the measurement head is fairly simple, and all sensitive and expensive parts can be kept at a more protected location. The CLR used is a modification of a system developed at FOI used for long-distance target recognition of vibrating objects such as vehicles [9, 10]. The original system can measure vibrations up to distances of km.

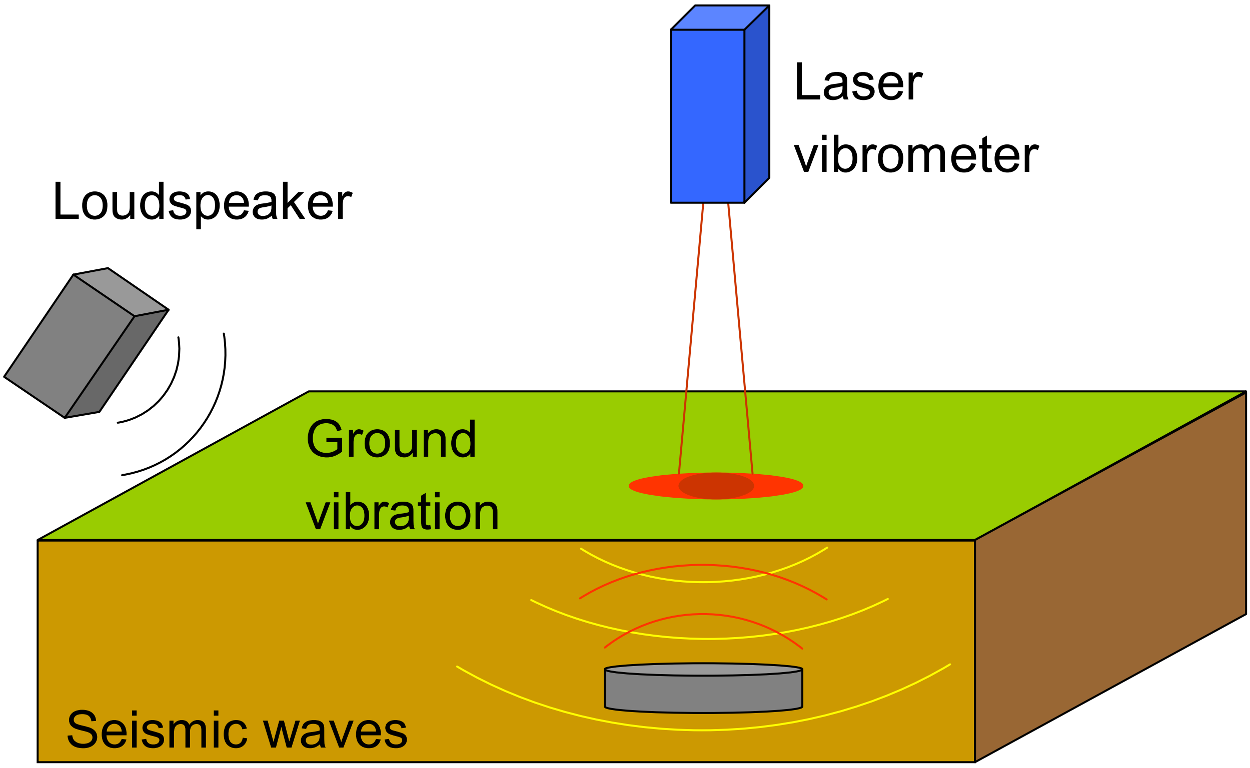

Figure 1. The figure show the principle of mine detection based on CLR measurements of acoustically induced surface vibration.

In this report we describe a project that was funded by the FOI Innovation board. The project aimed at exploiting the use of laser vibrometry for detection of buried mines using laser vibrometry. A working remote detection system for buried mines based on laser vibrometry would be of great national and international value. So far, only some initial experiments have been conducted in an indoor test site dedicated to testing mine detection equipment, mainly ground penetrating radar. Tests were made on a number of buried objects. The equipment that was used in the experiments is described in Section 2. The measurements are described in Section 3 and the results are presented in Section 4. In the concluding discussion in Section 5 some topics for future work are mentioned.

2. System description

2.1 Acoustic equipment

For the acoustic source, we used a signal generator from Neutrik (Minirator MR1), which delivered a bandwidth limited white noise signal from 20 Hz to 20 kHz at a level of 4 dBV. This signal was pre-amplified by an equaliser from ECLER. The frequency band of the final acoustic signal was selected on equaliser. The low limit was always 50 Hz, while the upper limit was mostly set to 800 Hz. However, for some of the measurements, the upper limit was set to 200, 400 or 1200 Hz. The signal from the equaliser was amplified in a CROWN SR1 (2300W) output stage. An EAW FR250z (2×15'') loudspeaker directed the acoustic sound down to the ground at an angle of about 30°. It was possible to reach a total sound pressure level of approximately 120 dB with the system. Most of the measurements were performed at a total sound pressure level of 115 dB in the frequency band of 50 to 800 Hz. Both the output stage and the loudspeaker were kindly supplied by the company Sennheiser AB. Pictures of the output stage and the loudspeaker are found in Figure 2.

Figure 2. Pictures of the output stage and the loudspeaker, respectively.

The sound pressure was monitored by a microphone (MiniSPL) and a sound pressure level analyser (Minilyzer ML1) from Neutrik. The microphone was placed approximately 0.5 m behind the objects, seen from the loudspeaker, and about 0.2 m above the ground. Pictures of the equipment are found in Figure 3.

2.2 Laser vibrometer

The CLR system used in these tests is a modification of a multi-purpose CLR for range, speed, vibration, and wind measurements [9]. The new system is bi-static and the main application is long-distance vibration measurements [10]. The schematics are shown in Figure 4. For the mine detection measurements, we used a 250 m long reinforced fibre cable between the measurement head and the main parts of the system, since we wanted to keep all the sensitive parts at a distance from the test ground. The fibre cable was exposed to high sound pressure levels. Although the reinforcement of the cable protected the fibres from acoustically induced noise to some extent, we decided to let the local oscillator (LO) arm pass through the cable. In this way, the effect of the sound pressure is almost negligible, since both arms of the interferometer are exposed to the same acoustically induced disturbance.

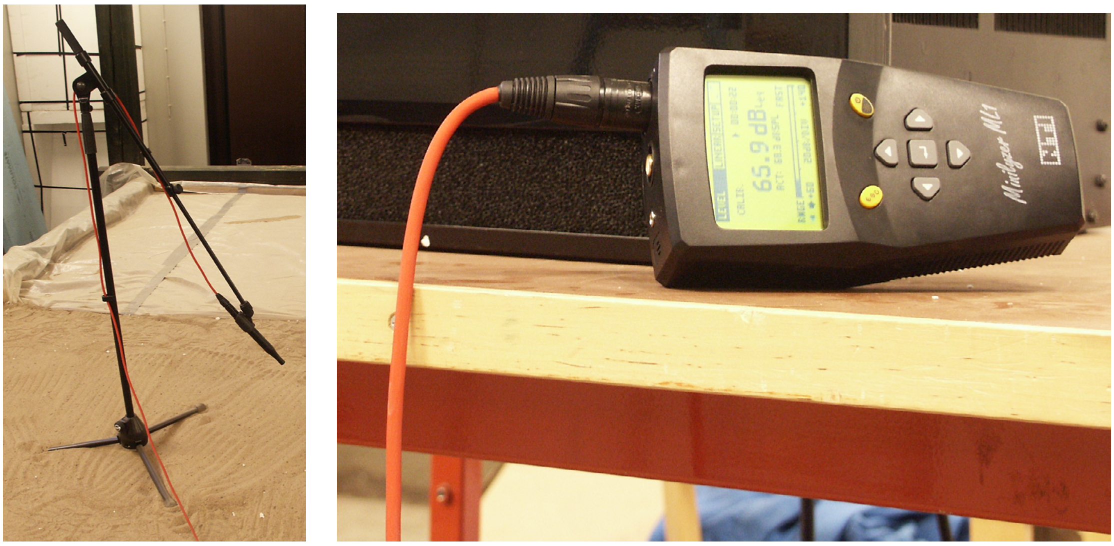

Figure 3. The microphone and the sound pressure level analyser.

We used the same settings of the CLR in all our measurements. The laser power was approximately 2 mW, the output power of the Erbium-doped fibre amplifier (EDFA) was 0.8 W, the acousto-optic modulator (AOM) shifted the frequency with 25 MHz, the Radio-Frequency (RF) mixer down-converted the electrical signal from the detector to 200 kHz, the cut-off frequency of the Low-Pass (LP) filter was 1.9 MHz. The Data Acquisition Card is 8 bits A/D-Card with the maximum sampling frequency of 1 Gbit/s and maximum storage capacity of 2 MSample. In all our measurements, we collected data for 1 s at a rate of 1Mbit/s, i.e. 1 MSample per point measurement. The focus and the overlap of the transmitter and receiver beams were aligned by transmitting laser light through both the telescope lenses. The diameter of the laser spots on the ground were less than 1 mm. Further details of the system can be found in Ref. [10].

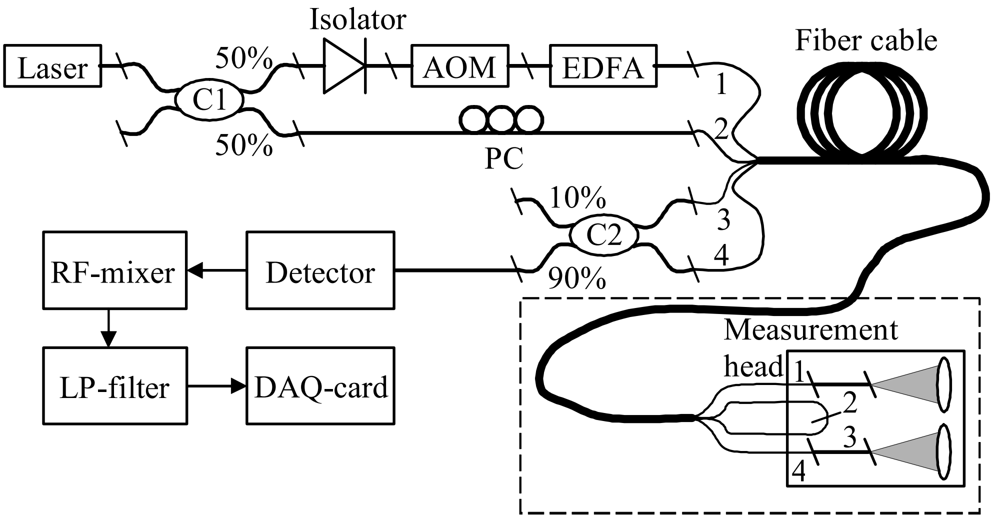

Figure 4. Schematics of the bi-static fibre-based coherent laser radar used in the experiment.

2.3 Signal processing

The processing of the vibrometry signal in order to find the frequency characteristics of the buried mines is described in the following. The acquired signal in each measurement point, see Figure 5, consisted of 1 million samples acquired in one second.

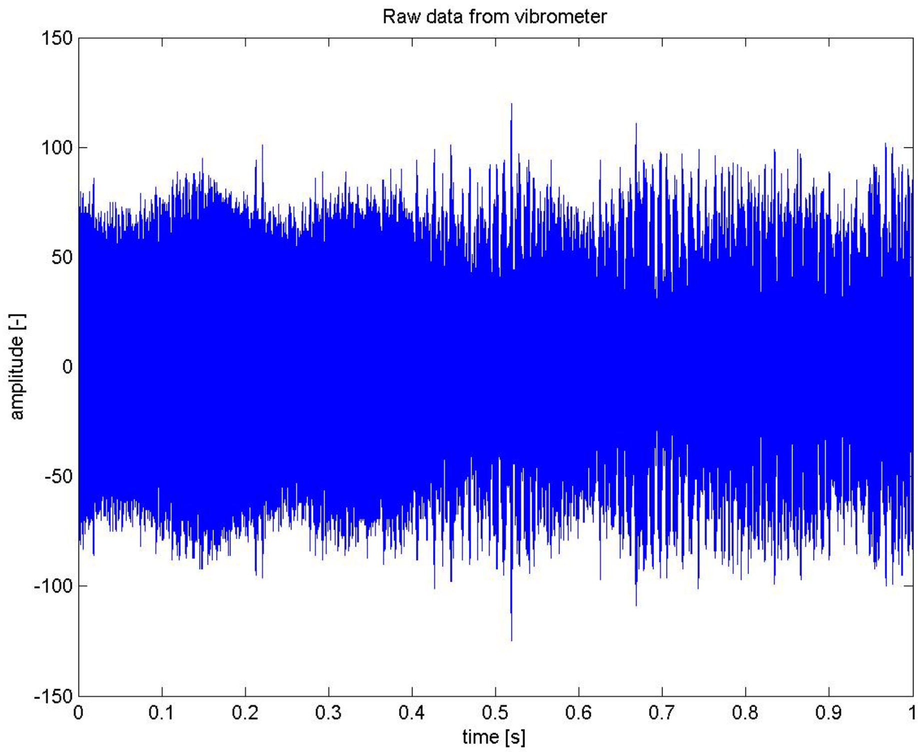

Figure 5. The raw signal as it was acquired from the measurement system.

The signal was divided into parts of 4096 samples, with 75 % overlap. This resulted in a time resolution of about 1 ms, with averaging of the closest 4 ms. The division was done in order to reach the optimum relation between the needed calculation power and the resolution in the calculation. On each part of the signal a Hanning window was applied to reduce the truncation effects through the next step, which consisted of a discrete Fourier transform without zero padding. Only the absolute value and not the phase was regarded and to reduce the calculation time, only the left half of the Fourier transform was kept for further calculation steps. The resulting spectrogram frequency resolution was about 250 Hz, corresponding to a velocity resolution of about 0.2 mm/s at the current wavelength (1550 nm), see Figure 6.

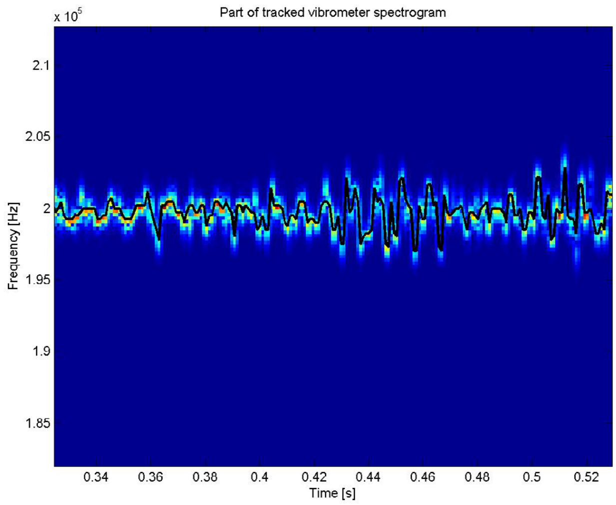

Figure 6. An enlarged part of the spectrogram with the tracked frequency peak as the black line. The carrier frequency can be seen at about 200 kHz.

With the Fourier transform calculated for each signal part, see Figure 7, the frequency peak in each part was tracked throughout the complete signal, see Figure 6 and Figure 7. The method to determine the frequency peak was through calculation of the inertia point. Since some signal parts can contain strong peaks not associated with the vibration, effort were made on excluding abnormal frequency jumps in the peak tracking.

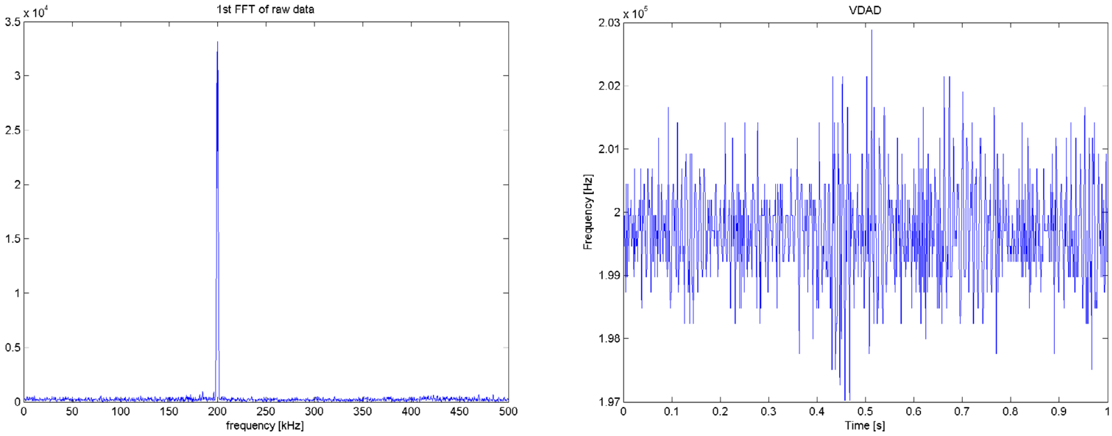

Figure 7. Left: The first Fourier transform in the sequence. Right: The tracked VDAD during a complete measurement.

The tracked signal represented the VDAD (vibrometer-derived acoustic data) time series. The data was AC filtered to remove the frequency offset due to the constant frequency shift. The VDAD signal, as shown in Figure 8, was windowed by a Hanning window followed by a Fourier transform with some zero padding (filled up to 8192 samples) to increase the frequency resolution.

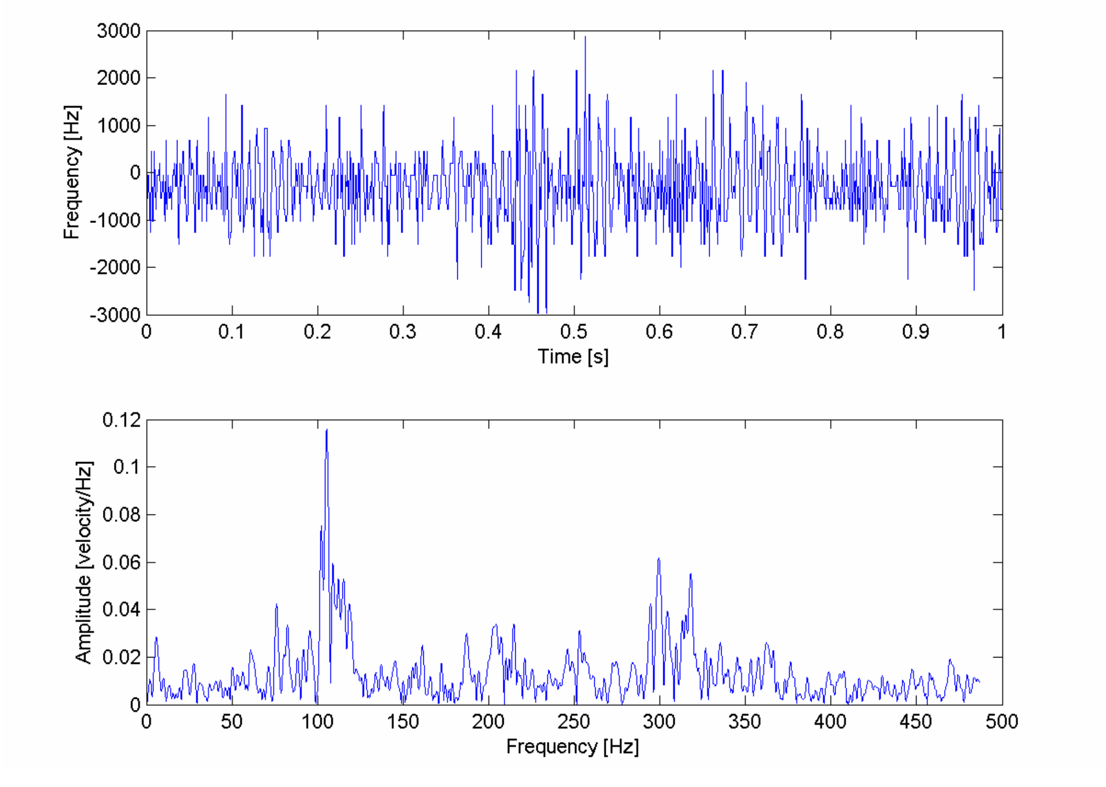

Figure 8. The AC-part of the VDAD (top) and the corresponding Fourier transform (bottom).

Normally, the vibration peaks were detected by quadratic interpolation of the vibration spectra. Though in the case of mine detection the frequency peaks are much wider and since we also want to examine the spatial distribution of the mine a more practical presentation is frequency imaging. Frequency imaging is a representation where each image shows the vibration energy for each frequency interval, see Figure 9, which in our case was 10 Hz wide with 5 Hz separation resulting in an overlap.

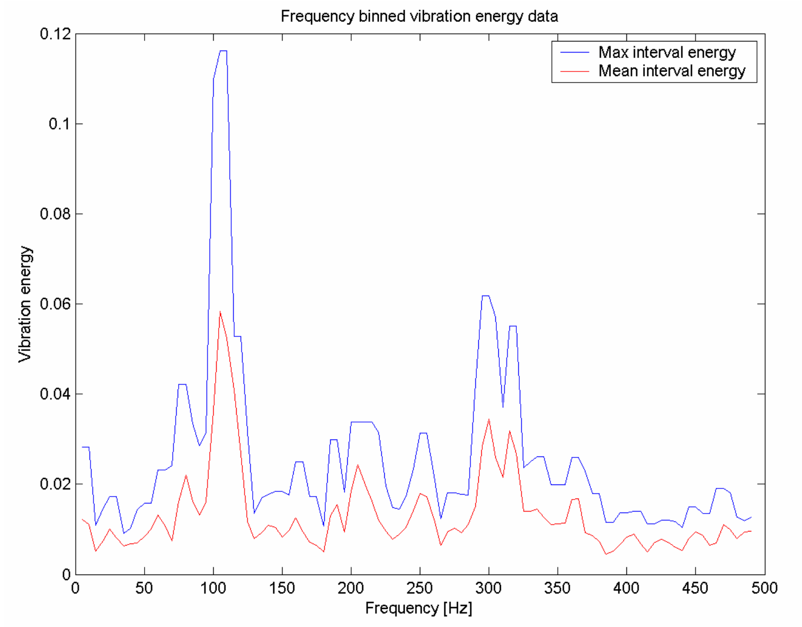

Figure 9. The vibration energy binned into frequency intervals. Inside each interval both the energy peak and the mean energy is determined.

According to the spatial matrix of measurement points during the data acquisition, the binned VDAD spectra were merged into images representing different vibration frequency intervals, as shown in Figure 10.

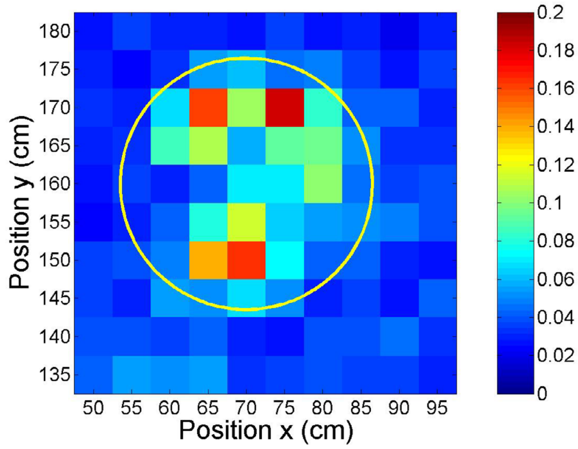

Figure 10. An example of a vibration image representing the frequency interval 88-113 Hz

Some other methods to extract the vibration spectra were also tested described below. These methods were not necessary for the mine detection problem but mere a test to reach a more stable and accurate calculation.

Software demodulation according to Ruck *et al.* [11] was briefly tested. The calculation was not stable enough, resulting in drop-outs in the vibration frequency images. The reason was probably the derivation of a too noisy signal. Another aspect is that the carrier frequency has to be steady and well known to be able to use this method.

A multi peak tracker was also developed and evaluated, to detect simultaneous peaks through the spectrogram. The parameters for this peak tracker were hard to tune and though this tracker has potential to be interesting, the time required to solve the problems was not available. For more information about this and some other evaluations of methods, see Ref. [12].

2.4 Test site

The measurements were performed in a room dedicated to the testing of mine-detection sensors, mainly ground-penetrating radars. An approximately 4×4 m square and 1.5 m high wooden frame is situated on a concrete floor. Our measurements were performed with the frame filled with dry sand, which could practically be characterized as desert sand. Above the frame, a coordinate table is installed. The measurement head was mounted on a vertical aluminium beam of the table, see Figure 11. The servomotors of the coordinate table allowed us to measure on the same spots in consecutive scans. The sound system delivered a flat sound level mainly in the frequency band between 50 to 800 Hz, with total sound pressure levels up to 120 dB.

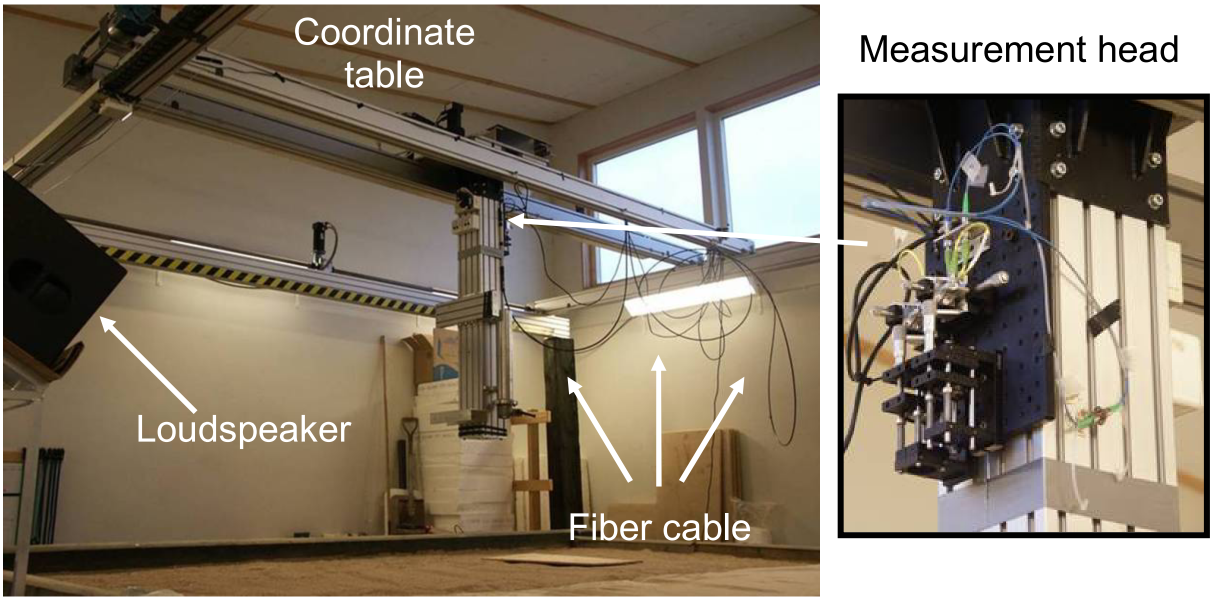

Figure 11. The test site with the sandpit, the loudspeaker to the left, the coordinate table and the vibrometer measurement head mounted on the moving arm. The inset shows the measurement head.

3. Measurements

The measurements were performed by scanning the vibrometer in an x-y-pattern over the area in the sandpit where the mines were buried. Typically, scans of 10×10 points with a point spacing of 5 cm were performed. Since the measurement head was moving during the scan, the fibre cable was not still. However, we could not see any influence of these movements in our results, mainly due to the fact that the LO is also present in the cable. The vertical beam itself was vibrating slightly after a movement of the coordinate table. To reduce this disturbance on the measurements, we had to wait for several seconds after the movement before data was collected. As a result, it took approximately 15 min to perform a 100 point scan.

3.1 Tested objects

We were mainly focused on testing anti-tank (AT) mines. The main objects investigated are shown in Figure 12. Two AT mines and one relatively flat stone were investigated. The mines are a low metal content and a metal AT mines, which have the diameter of 33 cm and 24 cm, respectively. The stone has a flat surface and a size of approximately 16×26 cm. Some measurements were also made of anti-personnel (AP) dummies and an empty soft drink can. These objects are shown in Figure 13.

Figure 12. From left to right are the three investigated objects: the low metal content AT mine, the metal AT mine and the stone.

Figure 13. The objects tested to resemble AP mines and similar sized objects. The three first objects are made of steel, beeswax, and styrofoam, respectively, and the last object was an empty soft drink can.

3.2 Problems and lessons learned

Our main problem in the measurements was to isolate the CLR system from acoustically induced disturbance. In the beginning, we used two single reinforced fibres to the transmitter and receiver telescopes, respectively. Although all equipment, except the measurement head, was place in another room than the test site and the loudspeaker, the noise in the measurements was too large to measure the ground vibration. We account the noise level to disturbance from the sound pressure in the 10 m long fibres from the main parts of the system to the measurement head. The fibres were exposed to a sound pressure level of around 100-120 dB, which washed away the Doppler shift information from the return of the ground vibration. We solved this problem by using a reinforced fibre cable, which let the LO arm of the interferometer pass through the same cable as the signal, as described above. This reduced the noise level so we were able to detect the ground vibrations.

For some reasons, we could not observe any clear resonances from the objects simulating the anti-personnel mines. This could possibly be explained by the material of the objects. None of the objects, except the soft drink can, had surfaces that work well as a membrane. The steel object had a very thick wall and, therefore, the membrane mode is difficult excite. The beeswax and the styrofoam objects do not have any rigid surface and, therefore, membrane modes are not possible. However, the soft drink can did not show any clear resonances either and that structure should have clear membrane modes. Therefore, it is more likely that the reason for not detecting small objects has another origin. One might be that the noise level is still too high to detect the vibrations from these objects. The tests were all performed at sound pressure levels around 115 dB. There might be a more optimal level. Furthermore, the frequency band of the acoustical excitation in the tests was from 50 to 800 Hz. Perhaps, there are better ways to excite small objects. Therefore, more extended work is needed to measure the vibration under different conditions and resolve the resonances of the objects. Other groups have shown that AP mines and small objects are possible to detect [4, 8].

Deeply buried mines were difficult to detect with the same acoustical excitation as shallowly buried mines. We show below that it is possible to resolve the mines with higher sound pressure levels and narrower excitation band. Further experiments should include tests of optimal excitation condition.

4. Results

Figure 14 - Figure 16 show the results of three scans of the sandpit with sound pressure levels of approximately 115 dB. The three different objects were buried just below the surface of the sand, approximately 2-4 cm below the surface. Furthermore, the objects were buried at the same position of the sandpit so the results could be directly compared. The scans were quadratic 10×10 points with an increment of 5 cm for each step. In each figure, the red lines indicate the spectra taken above the target and the blue lines are the spectra taken beside the target. The insets show the mean values of the points above and besides the objects. The amplitudes in the graphs are directly proportional to the maximum velocity in each frequency interval. The details of the signal processing can be found above in Section 2.3.

As can be seen in Figure 14 and Figure 15, the mines show clear resonances at around 100 Hz. The stone in Figure 16 does not show any pronounced resonance. This conclusion becomes even clearer in Figure 17, where the ratio between the mean vibrations above and beside the objects is plotted. The vibrations when measuring on the mines are almost three times larger than the vibrations off the mines at the frequencies around 100 Hz, while the vibrations on the stone are always less than 1.5 times larger than off the stone. The peaks at approximately 300 Hz, which are present in all spectra, are discussed below.

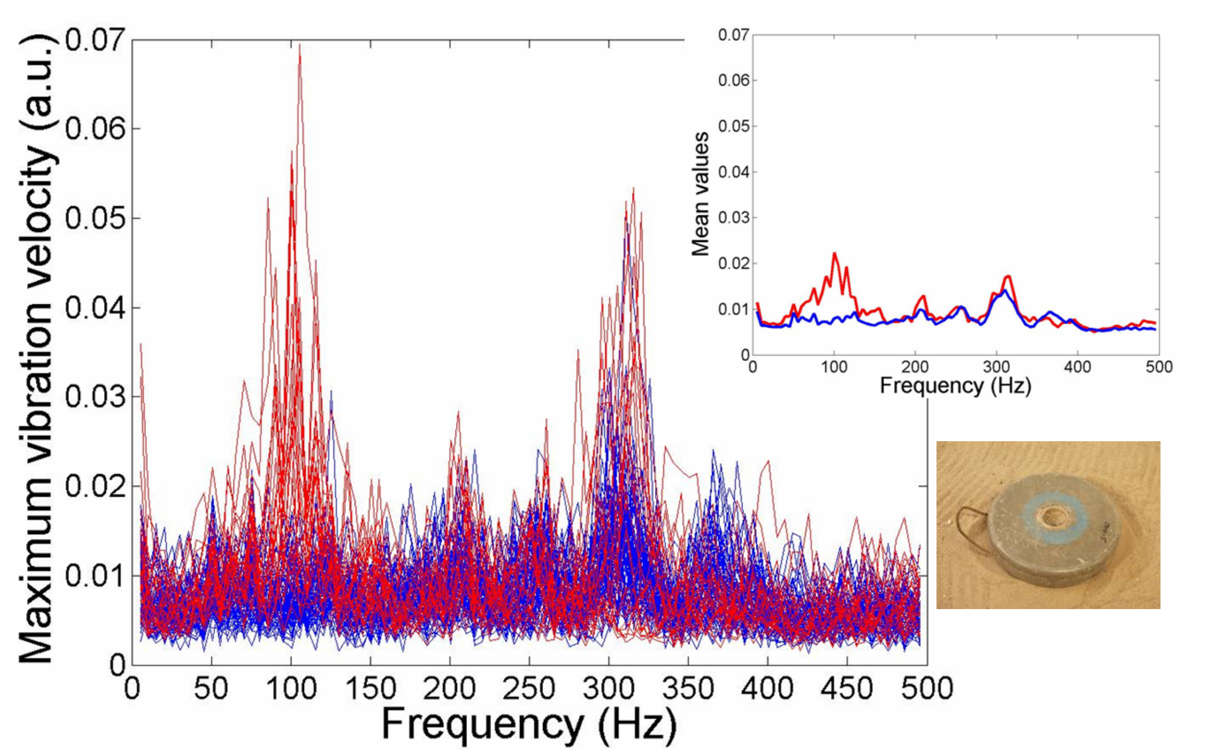

Figure 14. Vibration spectra taken on (red) and off (blue) the low metal content AT mine. The insets show the mean values of the vibration spectra and the mine, respectively.

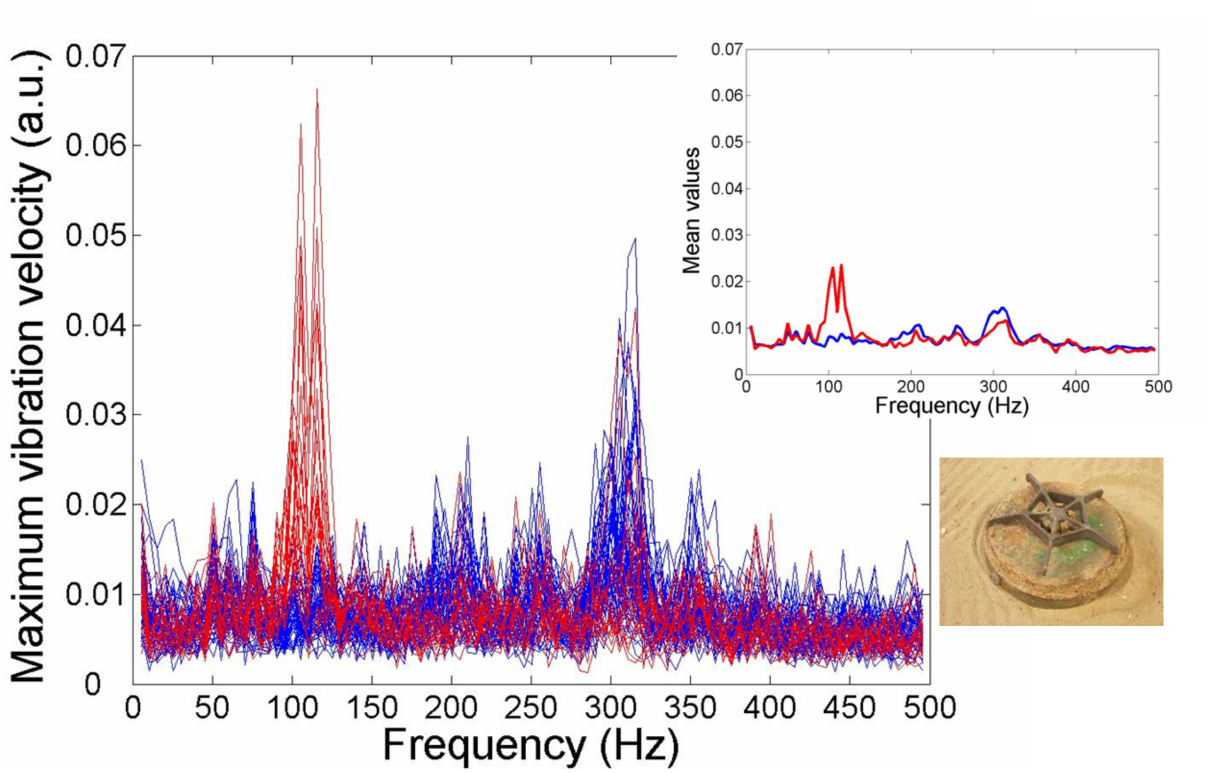

Figure 15. Vibration spectra taken on (red) and off (blue) the metal AT mine. The insets show the mean values of the vibration spectra and the mine, respectively.

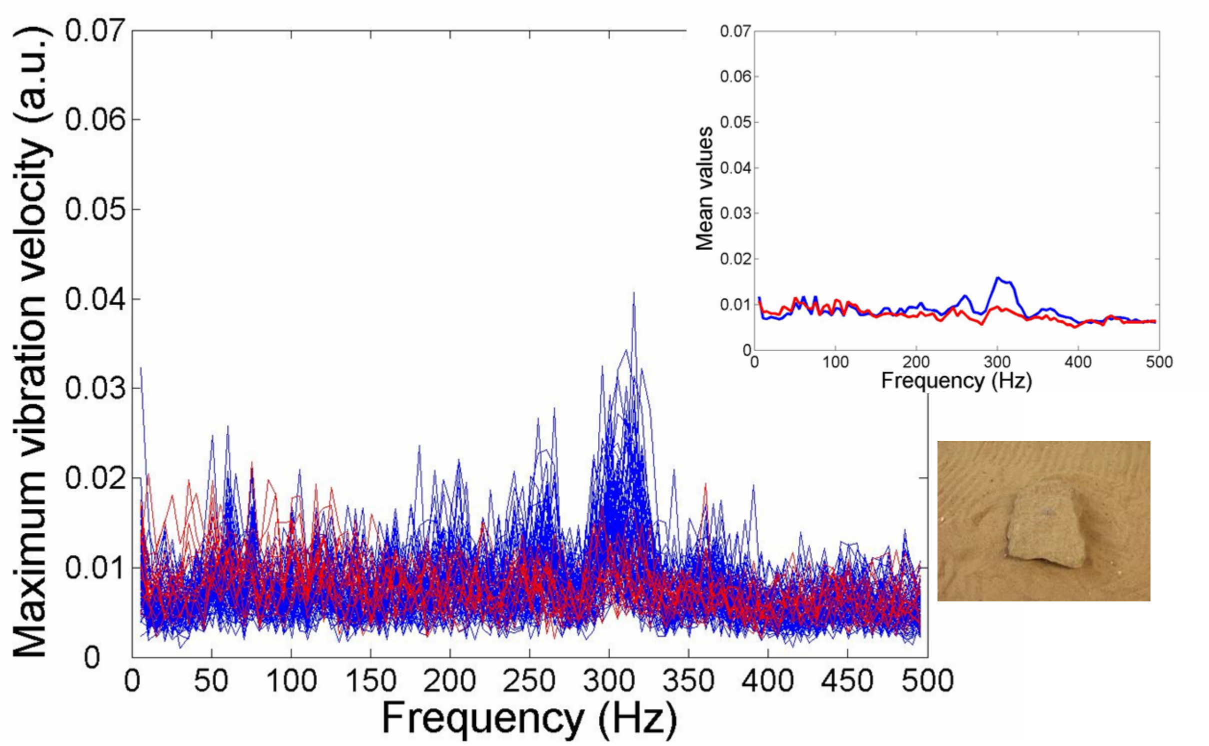

Figure 16. Vibration spectra taken on (red) and off (blue) flat stone. The insets show the mean values of the vibration spectra and the stone, respectively.

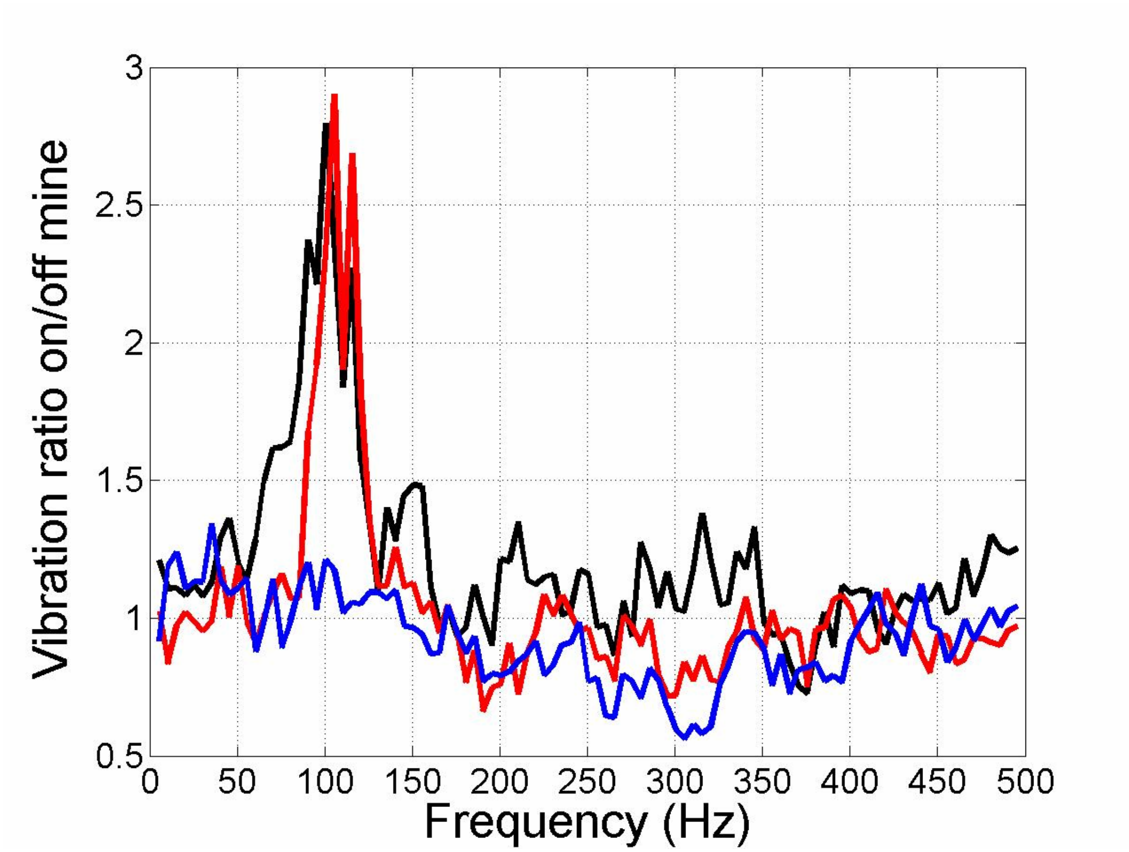

Figure 17. The ratio between vibrations above and besides the objects. The black, red and blue curves show the results for the low metal content AT mine, the metal AT mine and the flat stone, respectively.

In a real situation, the positions of the mines are not known and, therefore, it is not possible to compare the vibrations above and beside the mines as we have done above. Therefore, we have plotted the vibration images of the scans discussed above. The results are shown in Figure 18 - Figure 20. The figure shows the sum of the vibrations in the frequency span from 88 to 113 Hz (5 bins) for the spectra in Figure 14 - Figure 16. We can see that the extension of the vibrations at the surface of the sand is closely related to the area of the mines. Surprisingly, some spots above the low metal content AT mine show much less vibration than other spots. We believe that it can be explained by inhomogeneity of the mine. The mine consists of a plastic shell filled with concrete. The filling was unevenly spread in the shell. When repeating the scan with the mine 90º rotated, the spots with less vibration were rotated in a similar manner. Vibration images of rotated the mine is found in the end of this section, where we discuss the deeply buried mines.

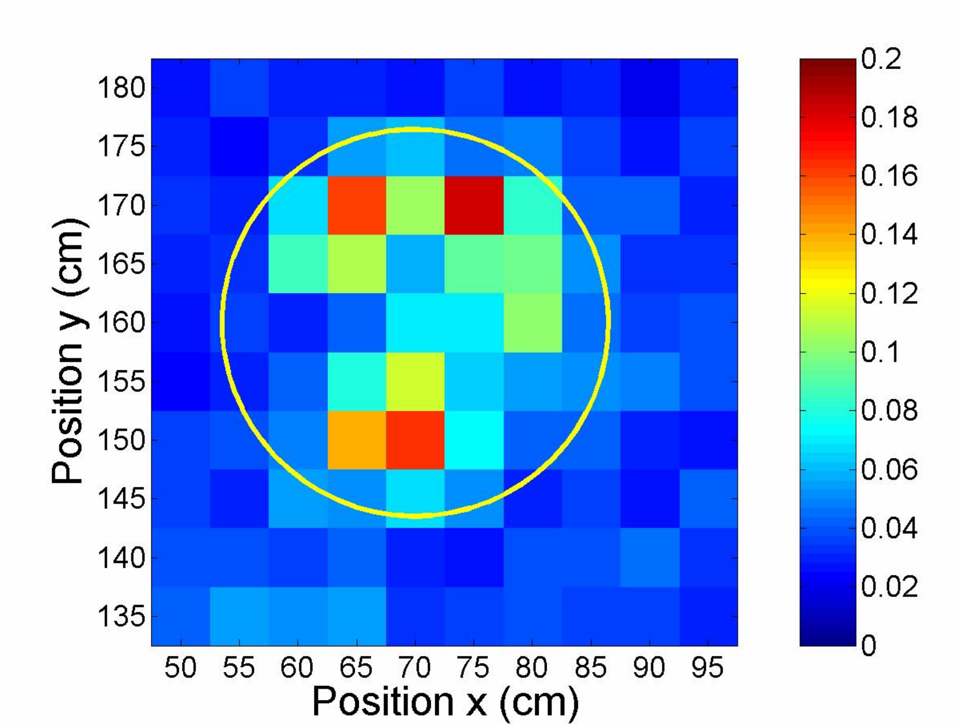

Figure 18. Vibration image of the low metal content AT mine in the frequency band of 88 to 113 Hz The yellow circle shows the position of the mine.

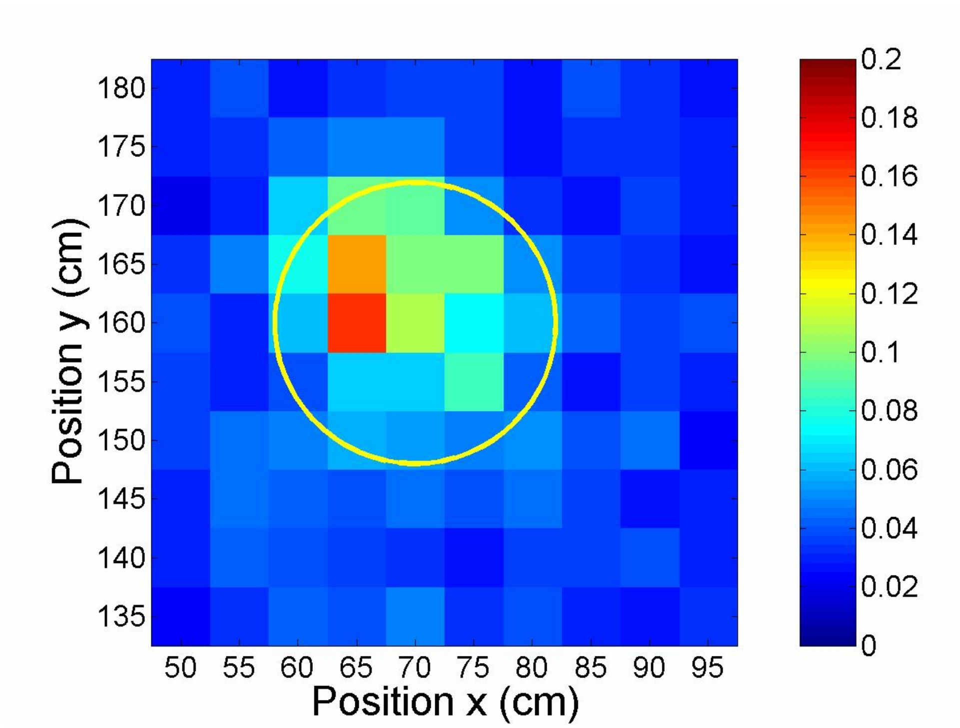

Figure 19. Vibration image of the metal AT mine in the frequency band of 88 to 113 Hz. The yellow circle shows the position of the mine.

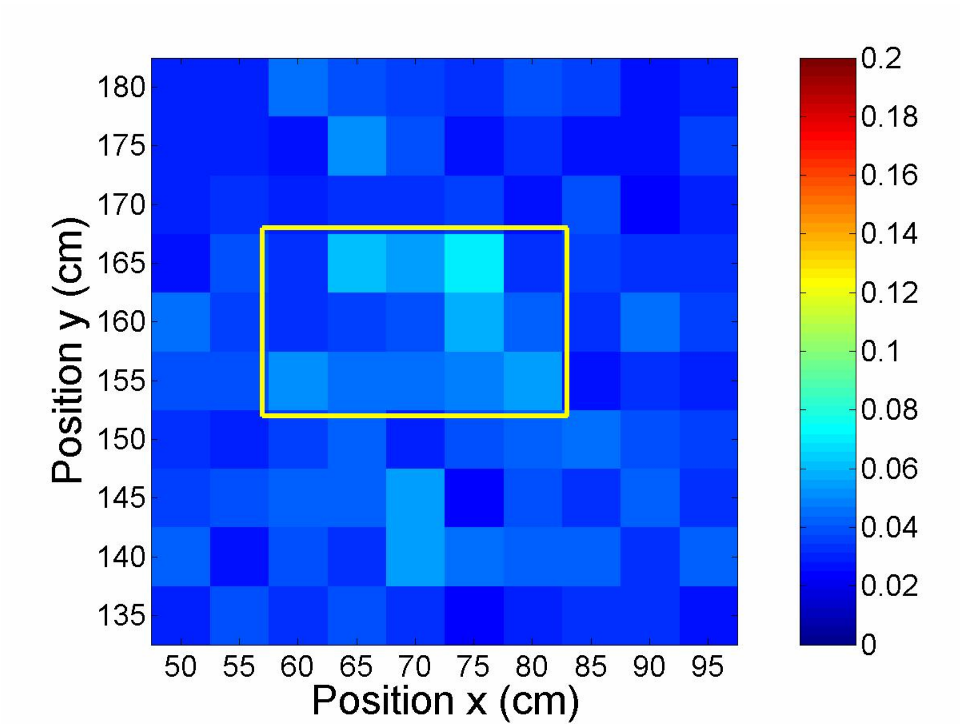

Figure 20. Vibration image of the stone in the frequency band of 88 to 113 Hz. The yellow rectangle shows the position of the stone.

In the all the spectra in Figure 14 to Figure 16, we saw increased vibrations at other frequencies than the resonances of the mines, mainly around 300 Hz. Vibration images of the objects in a frequency band centred around 300 Hz are shown in Figure 21. We cannot fully explain these peaks. However, we believe that it is an artefact of the measurements, perhaps with the exception of the low metal content AT mine, which show more vibration on the mine than off. It is likely that the vibrations are due to either be resonances in the sandpit itself or acoustically induced vibration in the coordinate table.

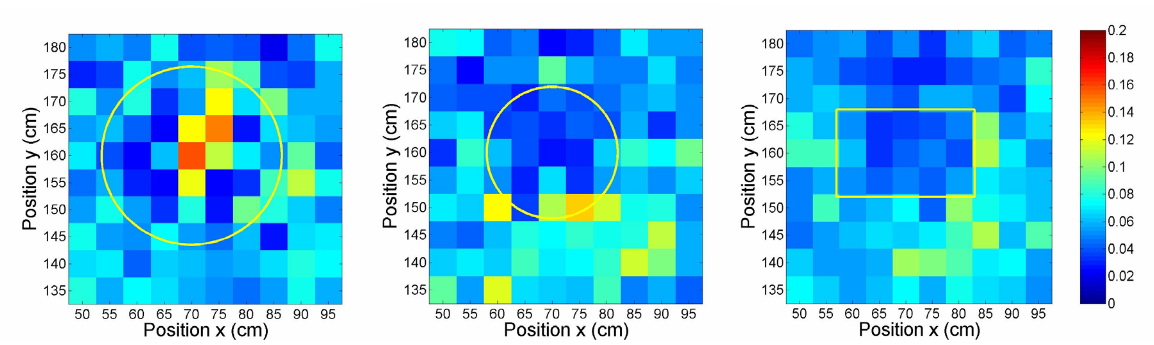

Figure 21. Vibration images of the low metal content AT mine, the metal AT mine and the stone in the frequency band of 288-313 Hz.

We investigated how the vibrations changed with different sound pressure levels of excitation. Obviously, the vibrations increased with an increase of sound pressure level. However, the ratio between the vibration on and off the mines did not increase in the same way, see Figure 22. The ratio off the resonance does not differ much for different sound pressure levels. However, on resonance (inset in Figure 22) the ratios differ more. The optimal sound pressure level for the low metal content mine buried about 3 cm below the surface in the sandpit was

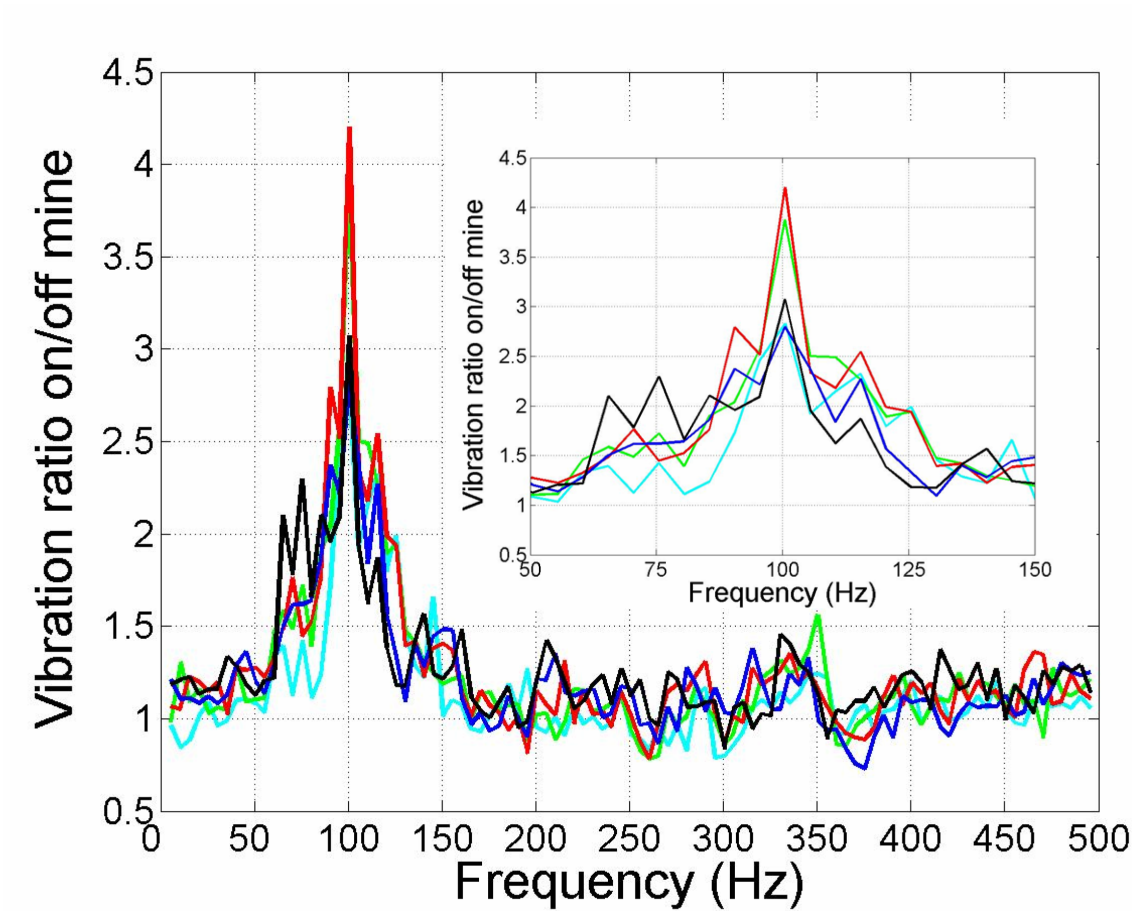

Figure 22. The ratio between vibrations above and besides the objects at different excitations. The black, blue, red, green and cyan curves show the ratio for the low metal content AT mine, at sound pressure levels of 118, 115, 110, 105 and 100 dB, respectively. The inset shows a magnification of frequencies around 100 Hz.

about 3 cm below the surface in the sandpit was around 105-110 dB. The ratio is about 30% larger at these sound pressure levels compared to both lower and larger levels.

When the objects were buried deeper, more than 5 cm below the surface, the velocity of the vibration on the mines became more similar to the background. Therefore, it turned out to be difficult to locate the mines. However, by increasing the sound pressure level at the resonance of the mines, the difference between the velocities on and off the mine became clearer. We achieved the higher sound pressure level by decreasing the frequency span of the sound source to be between 50 and 200 Hz. The total sound pressure level was still around 115 dB, but the level was approximately doubled between 50 and 200 Hz. The result for the low metal content AT mine buried approximately 6 cm below the surface is shown in Figure 23. The ratio between vibrations on and off the mine in the left image is about 2. In the right image, the ratio is almost 4. The higher ratio is partly due to higher vibration on the mine but also to lower vibration off the mine. Hence, larger contrast can be achieved by optimising the acoustic excitation. In these images the mine was rotated 90 degrees clockwise compared to the mine in Figure 14. Although the match is not perfect, the spots with lower vibration have also been rotated.

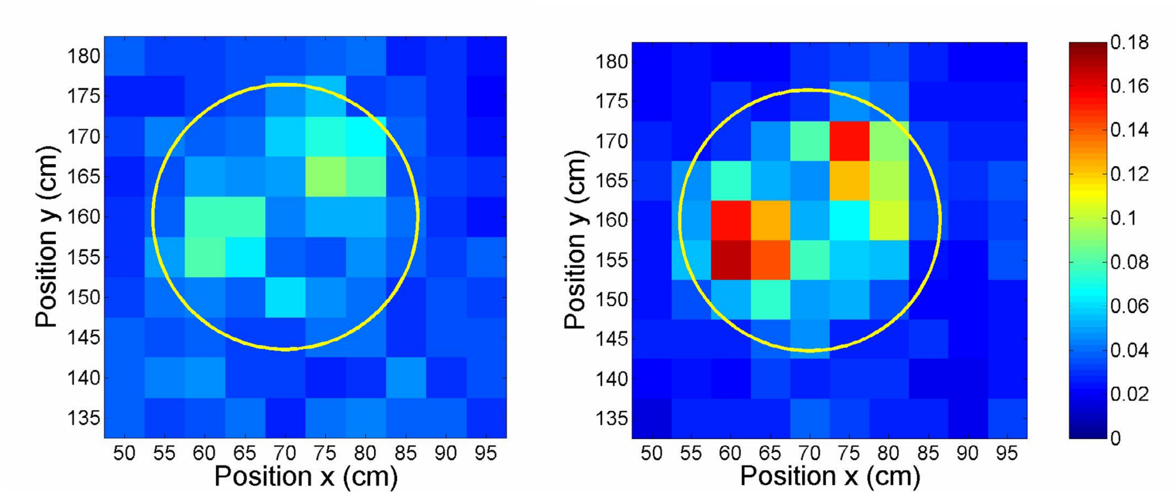

Figure 23. Vibration images of the low metal content AT mine buried 6 cm below the surface. The vibrations in five frequency bands (88-113 Hz) have been added. The total sound pressure level was approximately 115 dB in both cases. However, the excitation band in the left image was between 50 and 800 Hz, while the excitation was between 50 and 200 Hz in the right picture.

We also made some measurements on buried anti-personnel mines. However, there were not any clear resonances for these objects as there were for the AT mines. We suspect that the background noise is too large to resolve the resonances. Unfortunately, we did not have time to make thorough measurements on these objects, for example changing the sound pressure level and excitation band.

5. Discussion

We have demonstrated that buried land mines can be detected by measuring acoustically induced surface vibrations with a coherent laser radar. The detection methods works well for AT mines. The two AT mines that were used as test objects gave clear resonances around 100 Hz. The stone in the test did not show any clear resonances. The objects used to simulate anti-personnel mines did not show any clear resonances, unfortunately, no real AP mines were tested. This is a subject for further investigations. We need to get a better understanding of mine resonances and seismical waves. Further field studies are needed to evaluate the method under more realistic conditions, e.g. other types of mines and in various types of soil. Another factor that has not been tested is how vegetation on the ground affects the detection capability. Also, more experiments are needed to find the optimal acoustical excitation under different conditions.

Furthermore, we have shown that it is possible to keep the sensitive and expensive parts of the laser radar system far apart from the measurement head. By passing the local oscillator arm in the same fibre cable as feeding the measurement head, the system became fairly insensitive to both movements of the fibre cable and high sound pressure levels on the cable. However, we think that further improvements in noise reduction can be achieved by optimisation of the laser vibrometer for this application.

One important advantage with this method is the ability to perform remote detection of buried mines no direct contact with the ground. The method also can detect plastic mines. It could be used together with a metal detector to eliminate false alarms and to detect mines with low or no metal content. Furthermore, the geometry of the buried mines, as measured with the vibrometer, can be used to identify the type of mine.

The method also has the potential to detect anti-personnel mines, although the initial experiment did not succeed in detecting the simulated APM’s. However, detection of APM has been described in the literature.

Some disadvantages with the method are the slow area coverage capacity and the somewhat high sound level around the equipment. However, this may not be a limitation in the use of a capable system for mine detection. Also, the scanning speed has to be compared to the capacity of the present methods.

5.1 Future work

Some suggestions for future work are listed below.

- Perform experiments with anti-personnel mines (APM). In the experiment it was difficult to detect APM. In the literature however, such results have been reported [8, 13]. A further reduction of the noise level may be needed for this.
- Include registration of the phase of the acoustic generator (loudspeaker) simultaneously with the vibrometry signal.
- Investigate different aspect angles of the loudspeaker with respect to the ground surface.
- Investigate the impact of the frequency content of the acoustical signal (white noise, discrete frequencies, etc.). The acoustic power is used in the most effective way if the transmitted spectrum matches the expected resonance frequencies of the mines.
- Outdoor field trials should be conducted to evaluate the method. In the preliminary experiment in the sandpit, some disturbance from the walls of the sandpit could be assumed.

- Investigate performance in various types of soil. Only dry sand was used in the preliminary experiment. Other types of soil and water content should be investigated. Also, the impact of vegetation (grass, etc.) on the ground should be investigated.
- Compare detection with radar methods.
- Excitation with laser instead of loudspeaker has been described in the literature [14]. This could be experimentally studied. The possibility of destructing the mine with a laser could be investigated in connection with this.
- Detection of trip wires could be done with imaging 3-D laser radar. This could be investigated in a simple experiment.

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