Xi MAO [1], Ge-qiang Li[1], Chi WANG [2], Wei Ding[2]

University College of Mechatronics Engineering,Henan University of Science & Technology, Luoyang, China (1)
Department of Precision Mechanical Engineering, Shanghai University, Shanghai, China (2)

Experimental study of acoustic resonance technology for non-metallic mines detection

***Abstract**. An outdoor experimental system was designed to investigate the acoustic resonance method for non-metallic landmines detection. Firstly, the principle of acoustic-to-seismic coupling and its application in mines detection were overviewed. Then, the design process and experimental design of the system were discussed in details. Finally, experiments were performed with an antitank plastic coach mine. The results show that the buried mine can resonate at frequencies from 300 to 430Hz.*

***Streszczenie.** Przedstawiono możliwości wykorzystania metody rezonansu akustycznego do wykrywania min niemetalicznych. Przedstawiono projekt systemu oraz dane eksperymentalne. (**Eksperymentalne potwierdzenie możliwości detekcji min niemetalicznych metodą rezonansu akustycznego**)*

Keywords: acoustic-to-seismic coupling, acoustic resonance, mine detection.
Słowa kluczowe: rezonans akustyczny, wykrywanie min.

1. Introduction

The effective method for non-metallic landmines detection is a bottleneck problem in front of the international demining mission. The acoustic method shows promising increasingly that uses the mine's mechanical characteristic. Since 2001, Prof. Sabatier and Dr. Xiang have investigated the feasibility of acoustic landmines detection and established the linear resonance theoretical model[1-2]. Nearly at the same time, Dr. Donskoy studied the nonlinear resonance effect of the "soil-mine" system [3-4]. In 2002, Dr. Yu proposed the anti-resonance phenomenon of the "soil-mine" system[5]. In 2005, Dr. Zagari proposed the multi-modal resonance phenomenon of the "soil-mine" system[6]. However, there are few papers published about the design method of experimental systems.

In China, references [7-9] have described the principle of acoustic landmines detection. References [10-11] have discussed the indoor experimental system. However, such indoor experimental system fails to represent a real minefield environment although it can be used to verify the feasibility of acoustic landmines detection. Therefore, an outdoor experimental system has been developed for acoustic landmines detection. The design method for the system has been detailed. By through comparing the magnitude spectrum plots of the ground surface vibration velocity with mines, bricks, and nothing buried, we can verify the reliability of the proposed experimental system and the feasibility of the acoustic resonance technique for non-metallic mines detection

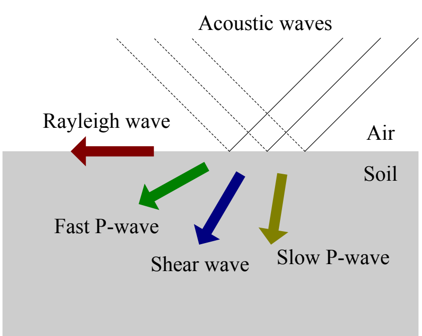

Fig. 1 Schematics of the acoustic-to-seismic coupling

2. Principle of acoustic mines detection

As shown in Fig.1, when an acoustic wave is incident to the ground surface, most energy is reflected back to the air. However, there is still a part of acoustic energy which is coupled into the ground. The acoustic waves will induce the ground surface vibration and different types of seismic waves, e.g. Rayleigh wave, shear wave, fast compressional wave (i.e. fast P-wave) and slow compressional (i.e. slow P-wave), etc. This phenomenon of acoustically induced seismic waves is termed acoustic-to-seismic coupling [12]. The energy of Rayleigh wave, shear wave and fast P-wave is mainly concentrated on solid phase matrix of soil, which means these waves cause stronger solid phase vibration and will mainly propagate through a buried mine. The energy of slow P-wave is mainly concentrated on fluid phase and will reflect or scatter intensively when striking a buried mine.

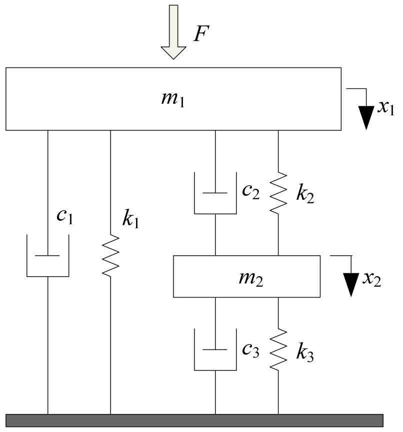

Fig.2 Schematic diagram of soil-mine resonance model

The mechanisms of the reflection and scattering of the slow P-wave usually cause too weak ground surface vibration to be used to detect a buried mine. However, a landmine has a higher acoustic compliance coefficient than the surrounding soil since it is composed of a container, a fuze and an air cavity. The buried landmine and its upper soil form a mass-spring resonance system as shown in Fig.2. The system will resonate under the incident acoustic wave, which means the energy of reflected or scattered waves will be enhanced and lead to the exacerbation of ground surface vibration. The existence of buried mine can be judged through measuring the distinct changes of the ground surface vibration. Especially for the plastic mines, the acoustic resonance technique is more suitable to detect them due to their bigger compliance. However, for the interferents, e.g. rock, stone and brick, etc., they may cause weaker ground surface vibration compared to the landmines since these interferents have a small compliance. Therefore, the acoustic resonance technique has a strong ability of identifying the non-metallic landmine theoretically.

As Fig.2 shown, F is an equivalent applied exogenic force, decided by incident acoustic wave. m_1 and m_2 are the equivalent mass of the soil on top of the mine and the mass of the mine's upper diaphragm respectively. c_1 and c_2 are respectively equivalent damping coefficients due to shear and compression of the soil. c_3 is the equivalent mine's damping coefficient. k_1 and k_2 are the equivalent equivalent spring stiffness factors due to soil's shear and normal stress respectively. k_3 is the equivalent spring stiffness factor of mine diaphragm. x_1 and x_2 are displacements of m_1 and m_2 respectively.

According to linear vibration theory, we can get the expression below:

(1) $$M\ddot{X} + C\dot{X} + KX = F$$

where X=*diag*(x_1, x_2) is a displacement matrix dependent upon ground surface and mine. $\dot{X}$ and $\ddot{X}$ are respectively velocity and acceleration matrixes. M=*diag*(m_1, m_2) is a mass matrix. $C = \begin{pmatrix} c_1 + c_2, -c_2 \\ -c_2, c_2 + c_3 \end{pmatrix}$ is a damping coefficient matrix. $K = \begin{pmatrix} k_1 + k_2, -k_2 \\ -k_2, k_2 + k_3 \end{pmatrix}$ is a stiffness matrix. F=*diag*(F,0) is an applied external force matrix. On condition of the harmonic sound excitation, $F=F_0\exp(j\omega t)$, the eq. (1) can be changed to the following form by Fourier transform theory:

(2) $$(K + j\omega C - \omega^2 M)X(\omega) = F(\omega)$$

Where $Z_d(\omega)=K+j\omega C-\omega^2 M$ denotes a displacement impedance matrix，and thus the velocity impedance matrix can be expressed as below:

(3) $$Z_v(\omega) = \frac{1}{j\omega} Z_d(\omega) = \frac{1}{j\omega} K + C + j\omega M$$

Velocity frequency response function can be written as:

(4) $$H_v(\omega) = Z_v^{-1}(\omega) = \begin{pmatrix} H_{v11}(\omega), H_{v12}(\omega) \\ H_{v21}(\omega), H_{v22}(\omega) \end{pmatrix}$$

Here, **adj**$Z_v(\omega)$ and **det**$Z_v(\omega)$ are respectively adjoint matrix and determinant of the impedance matrix. $H_{v11}(\omega)$ is the ground surface velocity frequency response. According to formulas above, amplitude-frequency characteristic function of $H_{v11}(\omega)$ can be derived below:

(5) $$\left|H_{v11}(\omega)\right| = \left(\frac{A_6\omega^6 + A_4\omega^4 + A_2\omega^2}{B_8\omega^8 + B_6\omega^6 + B_4\omega^4 + B_2\omega^2 + B_0} \right)^{1/2}$$

Where

$$A_6 = m_2^2, A_4 = c_{23}^2 - 2m_2k_{23}, A_2 = k_{23}^2; B_8 = m_1^2m_2^2,$$
$$B_6 = S_1 - 2m_1m_2S_2, B_4 = T_1 + 2T_2 - 2T_3, B_2 = U_1 - 2U_2,$$
$$B_0 = (k_1k_2 + k_1k_3 + k_2k_3)^2; S_1 = (m_1c_{23} + m_2c_{12})^2,$$
$$S_2 = k_{12}m_2 + k_{23}m_1 + c_{12}c_{23} - c_2^2;$$
$$T_1 = (k_{12}m_2 + k_{23}m_1 + c_{12}c_{23} - c_2^2)^2, T_2 = m_1m_2(k_{12}k_{23} - k_2^2),$$
$$T_3 = (m_1c_{23} + m_2c_{12})(k_{12}c_{23} + k_{23}c_{12} - 2k_2c_2);$$
$$U_1 = (k_{12}c_{23} + k_{23}c_{12} - 2k_2c_2)^2,$$
$$U_2 = (k_{12}k_{23} - k_2^2)(k_{12}m_2 + k_{23}m_1 + c_{12}c_{23} - c_2^2);$$
$$k_{12} = k_1 + k_2, k_{23} = k_2 + k_3; c_{12} = c_1 + c_2, c_{23} = c_2 + c_3$$

Judging from eq. (5), the amplitude-frequency function of the surface vibration velocity has maximum at four frequencies, i.e. resonance frequencies of the soil-mine system. Therefore, the model is a fourth-order resonance system as shown in Fig.2. When the frequency of the applied exogenic acoustic waves is equal to the resonance frequency of the system, the surface vibration velocity will be a maximum value that cannot be infinite due to the effect of damping, which just makes the surface vibration velocity much greater than the case without mines buried. It is noted that, although there are multi-resonance frequencies as shown in Fig.2 theoretically, the measured surface vibration velocity may not demonstrate all of them due to the more serious attenuation of acoustic energy at higher frequencies. In addition, the theoretical resonance frequency of the interferents (e.g. rock, stone and brick, etc.) will be at high frequency range due to their small compliance compared to the mines, which may not appear in the surface vibration velocity the same as the high resonance frequencies of buried mines do and thus is in agreement with the description of the fundamental theory of acoustic resonance technologies for mines detection discussed above.

3. Outdoor experimental system

Acoustic resonance landmine detection technique is essentially an information transmission or conversion including the process of coupling airborne sound wave into the ground, mechanically interacting with landmines distinctively, and then returning the effect to the ground surface vibration. The whole experimental system consists of acoustic wave emitting, ground vibration acquiring and data analysis and processing, etc.

The acoustic wave emitting system consists of a signal generator, a sound mixing desk, a power amplifier and a loudspeaker. The signal generator plays an important role in experiments since the quality of the output signal will have a direct effect on the ground surface vibration signal. The Tektronix AFG3022 Dual-channel arbitrary function generator is chosen as the signal generator. The sine wave from the signal generator should be pre-amplified before going into the power amplifier. A Yamaha MG8/2FX sound mixing desk is used as a preamplifier to make the output signal at a suitable level range. In the case of the choice of the loudspeaker, more attention should be paid to the response frequency range, power and cost. This system uses Soundking JB215 professional loudspeaker. In addition, a power amplifier should be chosen whose output power matches with the loudspeaker. This system uses PA2000 power amplifier (Shengbo Electronic Co., Ltd. Hangzhou, China).

The ground surface vibration signals contain vibration displacement, vibration speed, and vibration acceleration, etc.. These three types of signals can be used to characterize the ground surface vibration independently and can be detected by a laser Doppler vibrometer, a geophone array and an accelerometer respectively. They are interchangeable according to differential and integral calculus method. Taken the cost and precision into consideration, this system uses a 5×1 geophone array with 28Hz natural frequency, 28-1000Hz response frequency range and 138V/ms^{-1} test gain sensitivity. The output signal of the geophone array is collected into a computer by using an NI PCI5112 data acquisition card. Data are processed on the virtual instrument platform of LabVIEW.

According to the design above, the hardware of the whole system is shown in Fig.3, which is placed in a large outdoor lawn processed by weeding and excavating . The excavating depth is about 30cm. The opening place of the loudspeaker perpendiculars to the ground and the sound emitting unit is just above the geophone array with a relative height of about 50 cm. The landmine used in this system is a 69-antitank plastic coach mine. For security, the dynamite in the landmine is replaced by dry fine sand which has the same mechanical characteristics.

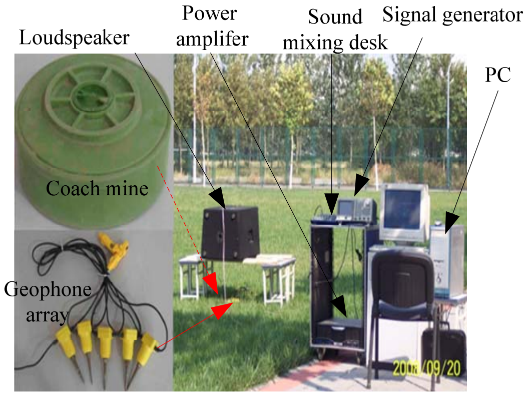

Fig.3 Experimental system of acoustic mines detection

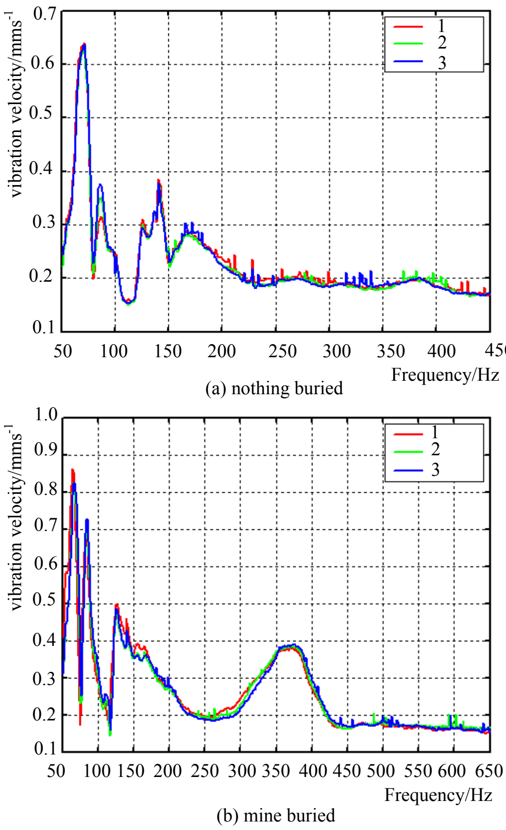

Fig. 4 The 3 measured ground vibration velocities

Before the experiment, the total potentiometer of the sound mixing desk and the channel volume potentiometer of the power amplifier should be turned to the lowest level. The sound mixing desk should be run before the power amplifier, which can avoid the overburning of the loudspeaker due to a possible pulse peaking. Then, by starting the signal generator and adjusting the potentiometers of the power amplifier and the sound mixing desk orderly, the presupposed single-frequency sine wave can be sent out and drive the loudspeaker. Finally, by running the LabVIEW software program, the detection signal can be acquired and processed. After finishing the ground surface vibration detection, the signal generator is adjusted to increase the output sine wave frequency of 1Hz. The applied C-weighted sound pressure level is above 110dB or 120dB in a wide frequency range.

4. Experimental Results

To ensure the output signal of geophone is not a result of direct coupling of acoustic wave, we used to hand the geophone just under the loudspeaker and found that the output of geophone was almost zero whatever the frequency of acoustic wave was. It shows that the following experiment data resulted from acoustic-to-seismic coupling ground vibration. In addition, according to the same parameters setting, we take measurements three times under off- and on- mine（the depth is 12cm）conditions respectively. As shown in Fig.4, the horizontal ordinate represents the incident frequency and the vertical ordinate represents root-mean-square value of the ground surface vibration velocity. From the Fig. 5, regardless of the existence of the landmine, the three measured curves appear identical, which proves that the system has good repeatability and thus ensure the reliability of the experimental data.

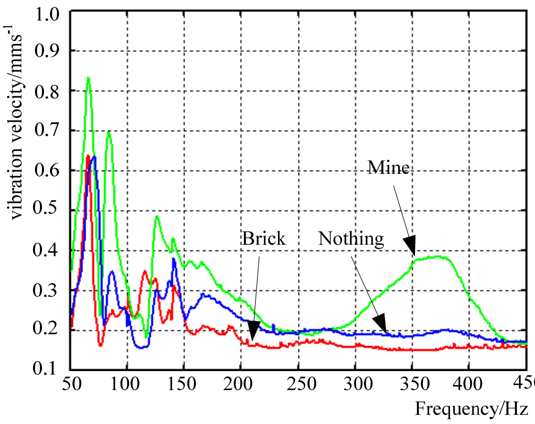

Fig. 5 Magnitude spectrum plots of the ground vibration velocities

To illustrate the mine's effect on the ground surface vibration, the ground surface vibration amplitudes spectra curves are compared upon the three conditions: nothing, mine and two bricks buried at 12cm depth beneath the ground. As Fig.5 shown, each curve is the average of three measurements. According to Fig.5, we can draw the following conclusions. First, the vibration amplitudes of these three curves are all smaller than 0.9mms-1 resulting from the low acoustic-to-seismic coupling efficiency. Second, the amplitudes of these three curves in the low frequency range below 200Hz are comparatively big and complex, due to the lower energy attenuation of the low frequency acoustic wave. Third, when the frequency is above 430Hz, the signal is becoming very weak due to the serious energy attenuation at high frequency. Fourth, almost throughout the whole frequency range, the on-mine signal amplitudes appear to be significantly larger than those off the mine. Especially from 300-430Hz, although the off-mine curve is dominated by noise, the on-mine signal amplitudes are relatively large and demonstrate the characteristics of resonance signal. However, when the bricks are buried, the measured surface vibration signal does not enjoy such characteristic but similar to the signals with nothing buried. Therefore, the effect of landmine on the acoustically induced ground surface vibration is obvious, which demonstrates that the acoustic resonance technique has the potential practical value for non-metallic landmines detection.

5. Conclusion and Discussion

In this paper, the basic principle of acoustic-to-seismic coupling and its application in landmines detection are overviewed. An outdoor experimental system for non-metallic landmines detection are detailed based on a loudspeaker and a geophone, including design method, experimental design and key issues. The experimental repeatability is also described. By through the comparison of the measured surface vibration signals with nothing buried, a mine buried, and two bricks buried, the effect of the mine on the surface vibration signal shows unique resonance characteristics, which demonstrates the potential application of acoustic-to-seismic coupling technique in the non-metallic mines detection.

However, acoustic technique for landmine detection is a complex and difficult task. Different acoustic parameters, different soil conditions, different landmine types and different burial depths will introduce different effect on the ground surface vibration signal. The coupling status between the geophone and the soil can also influence the signal amplitude and experimental repeatability. Therefore, the research in this paper is still at an early exploration stage. Relatiave experiments should be conducted with different mines, different soil conditions and different interferents, which is used to fully validate the feasibility of the acoustic resonance technique for landmine detection and study further on ground surface vibration signal processing and the imaging of buried landmines.

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***Authors**:*
Xi Mao, University College of Mechatronics Engineering,Henan University of Science & Technology, Luoyang, 471003, China.
E-mail: maoxi931208@126.com;
Ge-qiang Li, University College of Mechatronics Engineering, Henan University of Science & Technology, Luoyang, 471003, China. E-mail:hitligeqiang@163.com
Chi WANG, Department of Precision Mechanical Engineering, Shanghai University, Shanghai,200072,China.
E-mail: wangchi@sdu.edu.cn
Wei DiNG, Department of Precision Mechanical Engineering, Shanghai University, Shanghai,200072,China.
E-mail: dingwei@shu.edu.cn

The corresponding author:
Chi WANG, E-mail: wangchi@shu.edu.cn