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Detection of Shallow Underground Buried Object Using Air Vibration Probe

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An air vibration probe is a device for measuring acoustic impedance. It avails of a vibration of an air column and a delay line oscillation. Advantage of the probe is simple and contact-free detection. We suggest a shallow underground detection using the air vibration probe for its application. A two dimensional finite difference time domain (2-D FDTD) method and an experiment have been performed to evaluate the detectability of the probe. Sand is used for a medium of the ground and an empty polyethylene terephthalate (PET) bottle is used for buried object. Results of the calculation and experiment are almost agreed qualitatively. The 5th harmonic overtone is used for detection. The resonance frequency is derived by the 2-D FDTD method and the oscillation frequency is used in experiment. They become high when there is the PET bottle buried in underground. The depth of the object is shallower or the clearance between the probe and ground is wider, the frequency becomes higher. Thus, the frequency becomes high over the object when the probe scans the ground including the object. These results mean the probe can detect buried object in shallow underground. However, the response of the probe is affected by the irregularity of the ground surface.

1 Introduction

An air vibration probe is a device for measurement of acoustic impedance. The probe consists of a loudspeaker, a microphone, a voltage amplifier and a cylindrical tube. This configuration is similar to an impedance tube which is general device for measurement of acoustic impedance [1, 2]. It needs to cut a specimen to insert it into the tube, which is a problem because the specimen is destructed. The microphone needs to be moved the interior of the tube in the case of using a standing wave [1]. This requires time and cost to mechanically move a microphone. The measurement using the transfer function uses a number of microphones and heavy signal processing [2]. The air vibration probe can measure the acoustic impedance without any destruction. A closed circuit is formed by the feedback of the received signal at the microphone. So that a delay line oscillation is generated. A change of the transfer function affects the oscillation frequency. Thus, the microphone does not have to be moved. The measurement is shorten in the time and simplified.

We suggest that an underground detection for an application of the probe. The metal detector (MD) is used for sensing of landmines. The ground pulse radar (GPR) is used to detect the nonmetal object. A robot or a vehicle mounting the MD or the GPR is studied to detect landmines in safety, recently [3, 4]. Sugimoto studied underground detection using SH wave and transducer array in acoustic method [5, 6, 7]. Successful results are achieved in these methods, however the devices have got larger and more complicated as the detection has got higher performance. Therefore, there is availability for a simple device like as the air vibration probe to know its detectability. In this report, a buried empty polyethylene terephthalate (PET) bottle in sand is detected with the air vibration probe of contact-free. Simulation and an experiment are carried out to evaluate the property of the probe.

2 Principle of air vibration probe

A principle of the air vibration probe is explained by a vibration of an air column and a delay line oscillation. A sound propagation in a tube is shown in Fig. 1. A voltage in the pipe V as function of l and ω,

$$V = \alpha e^{-j\frac{\omega}{c}l} + \beta e^{j\frac{\omega}{c}l} . \tag{1}$$

Here, l is a distance from an input end to a measurement point on the transmission line, ω is an angler frequency, j is an imaginary unit and c is a phase velocity of sound. α and β are amplitudes of forward and backward sound pressures expressed as following;

$$\alpha = \frac{V_i}{e^{j\frac{\omega}{c}L} + re^{-j\frac{\omega}{c}L} + \frac{Z_i}{Z_0}\left(e^{j\frac{\omega}{c}L} - re^{-j\frac{\omega}{c}L}\right)} , \tag{2}$$

$$\beta = r\alpha , \tag{3}$$

where, V_i is a driving voltage, L is a length of the tube, Z_0 is a acoustic impedance of the tube, and Z_i is a synthetic impedance of an amplifier and a loudspeaker. A reflection coefficient r is

$$r = \frac{Z_r - Z_0}{Z_r + Z_0} . \tag{4}$$

A radiation impedance of the tube Z_r is approximately

$$Z_r = \frac{Z_0}{2}\left\{1 - \frac{J_1\left(\frac{\omega a}{c}\right)}{\frac{\omega a}{2c}} + j\frac{S_1\left(\frac{\omega a}{c}\right)}{\frac{\omega a}{2c}}\right\} . \tag{5}$$

Here, J_1 is the Bessel function of the first kind, S_1 is the Struve function and a is an inside diameter of the tube. The voltage V is derived by solving Eqs. (1) to (5). Though Z_r is the radiation impedance when the tube is in the free space, if there are some boundaries of the acoustic impedance

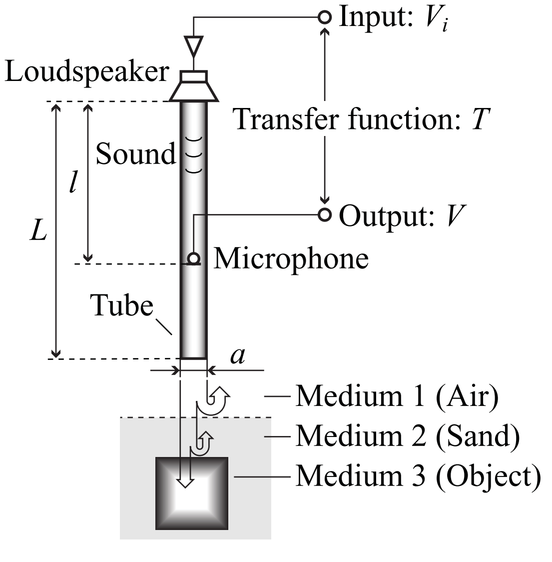

Fig. 1 Schematic view of air vibration probe in sensing.

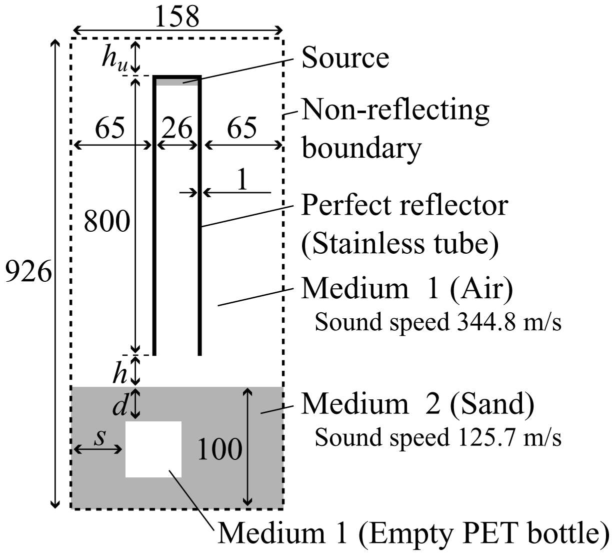

Fig. 2 Arrangement of 2-D FDTD method.

exist near the air vibration probe, *r* and *V* are changed.

An oscillation frequency of the delay line circuit is determined by a transfer function *T* which is derived from *V* and V_i. The oscillation condition is

$$|T| \ge 1, \tag{6}$$

$$\angle T = 2n\pi, \tag{7}$$

where, *n* is natural number. A frequency complying with Eqs. (6) and (7) is the oscillation frequency. When any boundaries of mediums of different acoustic impedance exist, a sound pressure is reflected from the boundary. For example, when there is a clearance between the probe and sand below the probe, the sound pressure is partly reflected at the boundary of the air and the sand. If some objects buried in the sand, the sound pressure that enters in sand is also reflected at the boundary of the sand and the object. *T* and the oscillation condition are changed because of the reflected sound pressure. The oscillation frequency is finally changed.

3 Simulation

An efficiency of the air vibration probe is evaluated with a two-dimensional finite difference time domain (2-D FDTD) method qualitatively. An arrangement of calculated domain and parameters of mediums are shown in Fig. 2. A sound speed in a medium 1 is 344.8 m/s corresponding to the air. A sound speed in a medium 2 is 125.7 m/s corresponding to the sand. Parameters of buried object are same to the medium 1 corresponding to an empty PET bottle. The existence of PET surface is ignored. A reflection coefficient in case of an incidence from medium 1 to the medium 2 is 0.12 in the measurement. A discretizing interval is 1 mm in space and 0.05 μs in time. The Gaussian pulse is inputted at the source. The transfer function *T* is calculated from the impulse response. $|T|$ shows some peaks which mean the harmonic overtones of the tube. The frequency of the 5th harmonic overtone is treated hereafter. *h* is a clearance between the stainless tube which is expressed with a rigid wall and the sand. h_u is the upper side clearance of the stainless tube, which is equal to 25 – *h* (mm). *d* is a depth of the buried PET bottle. *s* is the left side clearance between the PET bottle and the exterior boundary of the calculated domain. The frequency of 5th harmonic overtone in changing *h* from 4 mm to 20 mm at interval 2 mm and *d* = 5, 10 and 20 (mm)is shown in Fig.3. The PET bottle is under the tube at *s* = 50 mm. The frequency becomes high when *h* is large and *d* is small in all cases. It is expected to know the depth of the PET bottle in comparison because the curve of the frequency of each *d* does not cross each other. The deviation of the frequency is large when *h* is small. It is about 3 Hz at *h* = 4 mm. It shows the probe is more sensitive when the probe approaches to the ground. Difficulty increases when the probe gets away from the ground because the deviation of the frequencies is small.

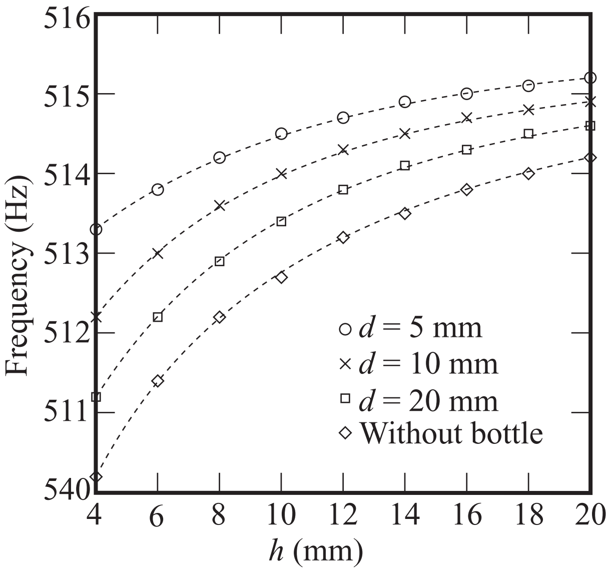

Fig. 3 Frequency of 5th harmonic overtone in various *h* and *d*.

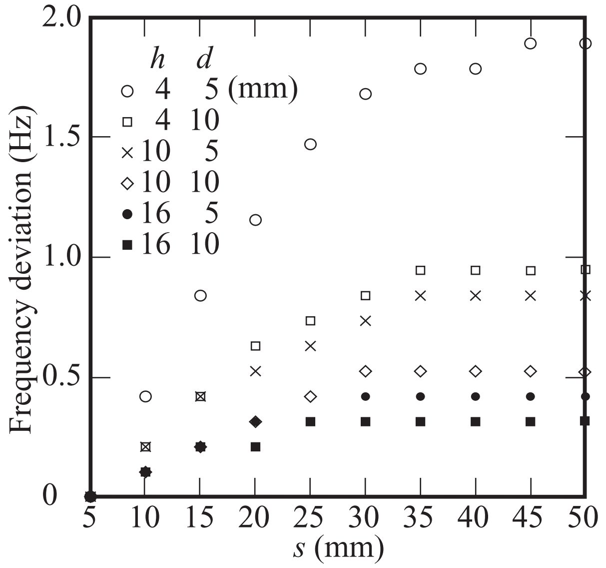

Fig. 4 Frequency deviation of 5th harmonic overtone in horizontal scan.

The frequency in changing *s* from 5 to 50 (mm) at interval of 5 mm, *h* = 4, 10 and 16, and *d* = 5 and 10 (mm) is shown in Fig. 4. Change of *s* is equivalent to horizontal scan of the probe. The left edge of the tube is just above the right edge of the PET bottle at *s* = 5 mm. The overlapping area increases gradually when *s* comes large. The vertical axis of

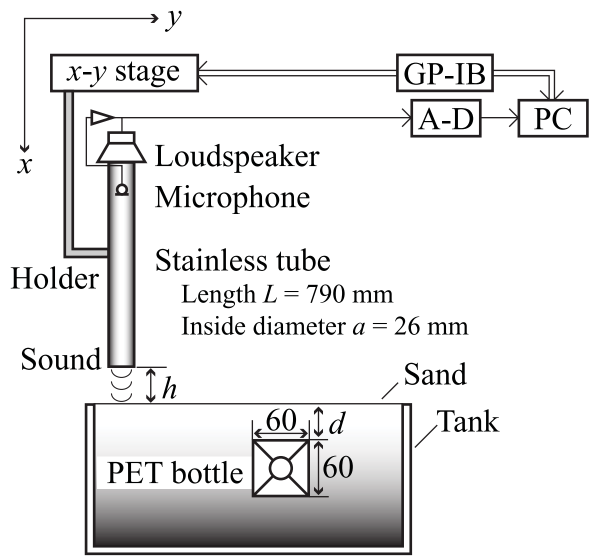

Fig. 5 Schematic view of experiment.

the Fig. 4 shows the variation of the frequency from the minimal frequency in each arrangement. It becomes large as *s* increases. This indicates the frequency becomes high when the PET bottle comes under the tube. The detection is easier in smaller *h* and *d* because the frequency deviation becomes larger. The maximal increment is near 2 Hz with *h* = 4 mm and *d* = 5 mm. It is not enough for human to distinguish the deviation. The rate of increase is large in case *h* is small. It means the probe is sensitive in small *h* as same as Fig. 3.

4 Experiment

An experimental apparatus is shown in Fig. 5. The diameter of the aperture of the loudspeaker (S.J ES-06603) is 64 mm. The microphone is an electrical condenser microphone, its shape is cylinder, and the diameter and height are both 10 mm. The inside diameter of the stainless tube is 26 mm and the length is 790 mm. The loudspeaker and the tube are attached by a board whose thickness is 10 mm. The PET bottle is 60 mm on the side and the height is 170 mm. The width of the tank is 330 mm, the length is 530 mm and the height is 290 mm. A room temperature is 23.7 °C in all experiments. The tank is filled with sand and the upper surface of sand has been evened out so as to be parallel to *x*-*y* stage. The air vibration probe is fastened on the *x*-*y* stage by a holder. The *x*-*y* stage is controlled by PC via a GP-IB interface. The oscillation frequency is logged after the oscillating signal is converted to the digital data by the A-D converter (National Instrument 6062-E) whose sampling frequency is 10 kHz.

4.1 Changing clearance between the probe and the ground

The oscillation frequency is measured under various heights of detection *h* and depths of the PET bottle buried in sand *d*. *h* is changed from 4 mm to 20 mm at intervals of 2 mm. *d* is changed to 5, 10 and 20 (mm), and the case without the PET bottle.

Results are shown in Fig. 6. The frequency has been high when the *h* is large or *d* is small. It agrees the result of the simulation shown in Fig. 3. Therefore, it is expected the air vibration probe can detect the PET bottle buried within 20 mm. However, the frequencies at *d* = 10 and 20 (mm) are almost the same. Thus, it is difficult for the air vibration probe fabricated in this experiment to distinguish a PET bottle buried deeper than 10 mm. It is different from the result of simulation. The attenuation is ignored in the simulation, which is the reason of these differences. The amplitude should be large to increase the detectable depth complimenting the transfer loss. The variation of the frequency is about 4 Hz at *d* = 5 mm. It is about 2 Hz in calculation. This difference is caused by the difference of the dimension. The calculation is performed in 2 dimension. Thus, the variation of the overlapped area of the diameter of the tube and the PET bottle is larger in the experiment than one of the calculation. 3 dimensional calculation is one of future works.

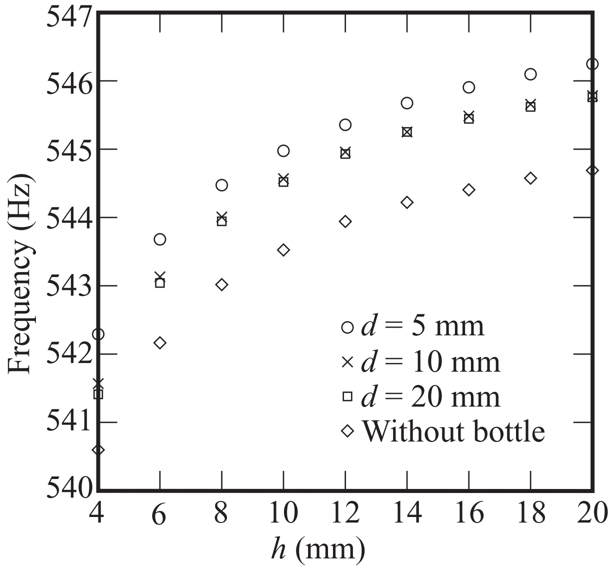

Fig. 6 Oscillation frequency in various *h* and *d*.

4.2 Buried object detection by scanning

The air vibration probe is scanned along the ground in practical using. Thus, it is important to evaluate the air vibration probe in the horizontal scan. The air vibration probe is moved above the buried PET bottle. *d* and *h* are varied 5 and 10 (mm) and 4, 10 and 16 (mm) respectively. The width of scan is 200 mm at interval of 5 mm.

Results are shown in Fig. 7. The vertical axis of the figure means a frequency deviation from an average frequency. The horizontal axis *y* means the position of the right edge of the stainless tube. Two vertical broken lines through graphs indicate the side limit of the overlapped area of the stainless tube and the PET bottle. The frequency becomes high when the probe comes over the PET bottle. The peak of frequency appears when the probe is scanned through the PET bottle. It agrees with the result of the simulation. Any evident peaks of the frequency deviation are not observed between the vertical broken lines when the PET bottle is not buried. It is possible to detect buried object by using the air vibration probe in shallow underground in the experiment.

Nevertheless, some problems exist. The frequency deviation is too small. The maximum deviation is about 0.3 Hz in *h* = 4 and *d* = 5 (mm). Additionally, the probe is

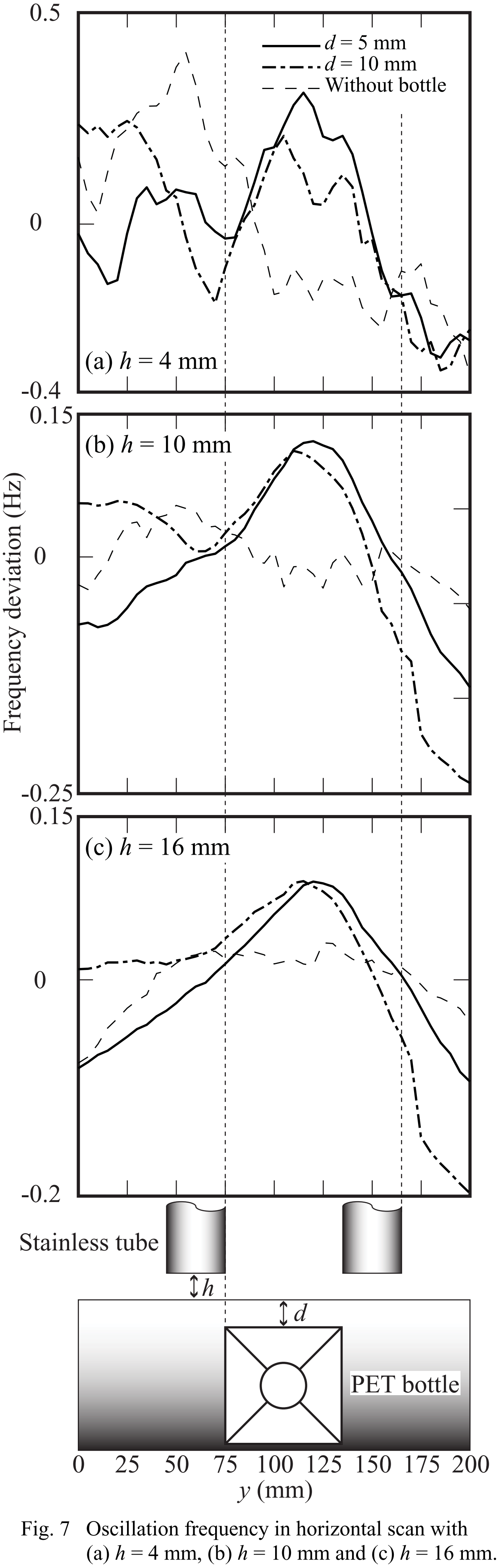

Fig. 7 Oscillation frequency in horizontal scan with (a) h = 4 mm, (b) h = 10 mm and (c) h = 16 mm.

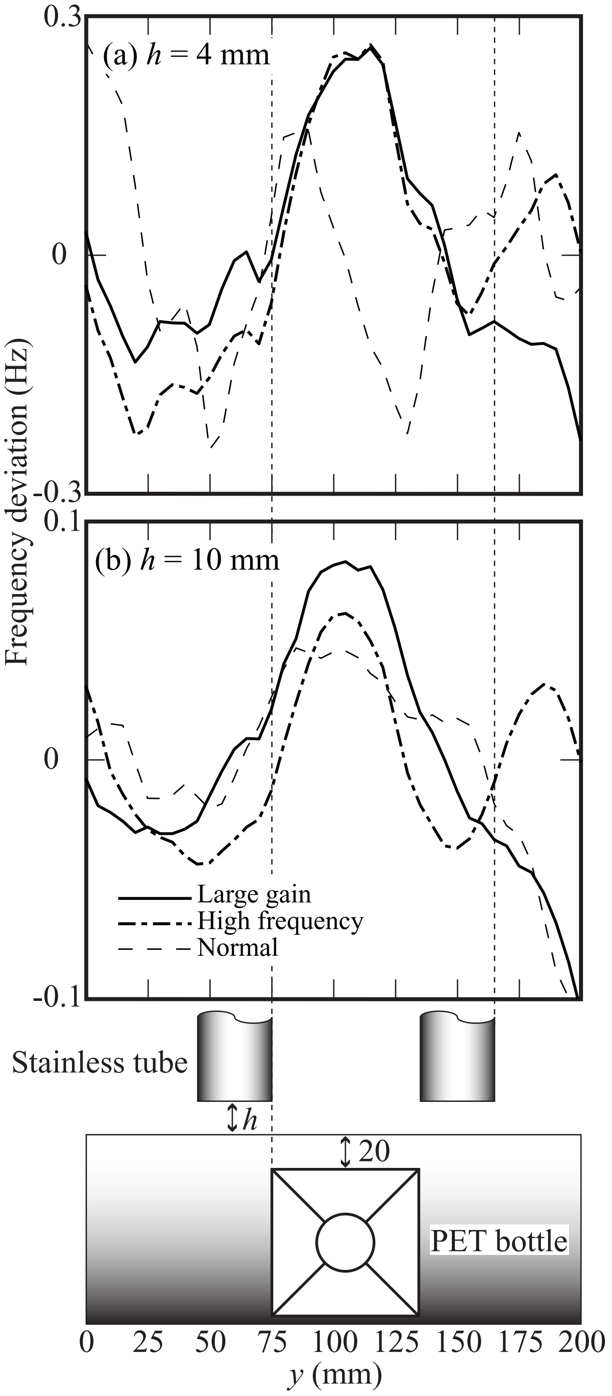

Fig. 8 Oscillation frequency in horizontal scan using louder and higher tone with (a) h = 4 mm and (b) h = 10 mm.

affected by the irregularity of the ground surface. It is difficult to determine whether the peak is caused by the buried object or the irregularity of the ground surface. The frequency of h = 4 and d = 10 (mm) makes a peak between y = 0 and 75 (mm) as shown in Fig. 7 (a). This is due to the slight concavity of the ground. The air vibration probe becomes more sensitive when h is smaller. However, it becomes more difficult to use the probe above an irregular ground.

4.3 Expansion of detectable depth

The detectable depth is an important property of the probe. Increases of $|T|$ is one of the available methods because the larger sound pressure is radiated from the probe. It also becomes larger when the oscillation frequency becomes high because the radiation impedance is almost equal to the acoustic impedance of the tube in such a case. The gain of the amplifier is increased to make $|T|$ large. An electric filter is used to make the oscillation frequency high. The probe is scanned over the PET bottle buried in d = 20 mm with changing h = 4 and 10 (mm). The amplitude of the delay line oscillation is 1.4 Vp-p and the oscillation frequency is about 550 Hz when the gain is enlarged. The amplitude is 1.2 Vp-p and the frequency is about 760 Hz when the filter is used. The measurement same as the former subsection is done for comparison. These three measurements are named as "Large gain", "High frequency" and "Normal" in order to prevent confusions, hereafter.

Results are shown in Fig. 8. The detection performances of "Large gain" and "High frequency" are better than "Normal" in Fig. 8(a) because the frequency peaks of these two methods appear over the PET bottle but "Normal" does not. Although the frequency peaks of three methods appear over the PET bottle in Fig. 8(b), "Normal" shows a blunt peak and "High frequency" shows a very small change. "Large gain" is the best method among three methods in this experiment because the peak is sharp and clear. It is necessary to evaluate about the shape or the circuit design of the probe for improvement.

5 Conclusion

We suggest a shallow underground detection using the air vibration probe. The performance of the probe has been evaluated by the 2-D FDTD method and the experiment. The frequency of the 5th harmonic overtone has been calculated. The oscillation frequency has been measured in the experiment. Results have shown some characteristic properties as following in calculation or the experiment.

(1) The frequency becomes higher when the clearance between the probe and the sand is large. If the empty PET bottle exists under the sand, when the depth of the PET bottle is shallower, the frequency becomes higher.

(2) When the probe has scanned the sand including the PET bottle in horizontal position, the frequency becomes high over the PET bottle.

(3) The probe has good detectability when the amplitude of the sound is large.

However, there are some problems which are the detectable depth is extremely shallow and the probe is affected by an irregularity. Enlargement of the gain of the amplifier is one of effective method to increase the detectable depth.

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