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ACCURACY IMPROVEMENT OF CEPSTRUM ANALYSIS FOR DETECTING PENETRATION OF FOUNDATION PILES USING ULTRASONIC WAVE

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Authors have been conducting a study in order to find a way to perform a non-destructive test on concrete objects with high accuracy and repeatability. Ultrasonic measurement was chosen for this.

In our previous research, arbitrary down chirp signals were inputted to concrete, using piezo-electric ceramics, and auto-correlation analysis was used to detect the reflection wave. Furthermore, when the obtained output waveform had the direct wave and the reflection wave mixed, the arrival time of the reflection wave was found out by using cepstrum analysis. However, cepstrum analysis tended to be effected by noise, and therefore it was not able to detect a reflection wave clearly. In this paper, in order to make this influence less effective, Langevin transducer was used instead of the AE transducer for inputting ultrasonic wave with stronger amplitude and average response method was applied before analyzing the waveform with cepstrum analysis. As a result of the experiment, it was confirmed that the clarity of the detection of a reflection wave improved by using Langevine transducer as its input.

Key Words: *geo-sensing, ultrasonic wave, foundation pile, non-destructive test, cepstrum analysis, Langevin transducer, and average response method*

1. INTRODUCTION

In civil engineering, especially in construction sites, it is essential to investigate the degree of damage and the depth of foundation piles and pillars. Currently, non-destruction measurement methods are being used in these cases because of time and money consideration. Ultrasonic wave and elastic impact wave methods are currently used as typical non-destructive testing methods to be applied to a concrete object such as a foundation pile for construction. The latter is performed with using a hammer as its input making this method inaccurate and hard to obtain the same result each time. Therefore, ultrasonic measurement method was chosen over elastic impact wave method to be applied in this study. However, by using the conventional ultrasonic measurement method, since the input is very small, the depth of the investigation is very shallow. Therefore, if it becomes possible to input ultrasonic wave vibration into the concrete foundation pile, deeper depth investigation with higher precision will be attained. Authors have designed a non-destructive measurement system, which uses two ultrasonic transducers as shown in Fig.1. One transducer is used as an input to transmit ultrasonic wave into the concrete object and the other is used to receive the reflection wave that comes back as an output. Two patterns of sensor settings can be seen in Fig.1 (a) and (b). First, the sensors are set as pattern 1 to measure the velocity of the ultrasonic wave in the concrete foundation pile using the known length. In this experiment, this method was applied to the major axis of the measuring object to obtain accurate velocity. Then the sensors are set as pattern 2 in order to measure the depth of the subject. In Fig.1 (a), foundation pile has no damage so only the depth is measured by the system. In Fig.1 (b) the foundation pile has a fracture on the path of the ultrasonic wave so the ultrasonic waves reflects back from there as well as the reflection wave from the bottom making it possible to estimate both the damage and the depth of the foundation pile.

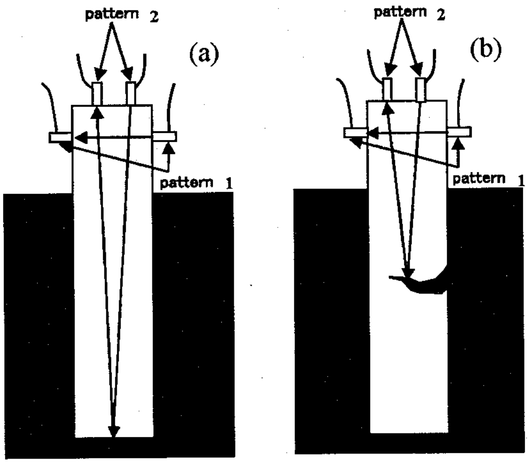

Fig.1 Foundation Pile Measurement

In our previous research, arbitrary down chirp signals were inputted to concrete using piezo-electric ceramics. However, the output wave received by the transducer contained a wave that have the direct wave and the reflection wave mixed together making it unable to estimate the arrival time of the reflection wave. [1-4)]

Therefore, a technique of separating the direct wave and the reflection wave in order to find out the arrival time of the reflection wave was developed.[1-4)]

Furthermore, when the obtained output waveform had the direct wave and the reflection wave mixed, the arrival time of the reflection wave was found out by using cepstrum analysis. [1-4)]. From these analyses, it was shown the possibility that the size of target can be estimated by using cepstrum analysis, even when the target size was unknown. This was compared to the case when auto-correlation was used as its method of analysis because an ideal strength of input had to be chosen to attenuate the direct wave in order to estimate the arrival time of the reflection wave.

However, cepstrum analysis was effected greatly by noise, and therefore it was not able to detect the reflection wave clearly[1-4)] . In this paper, scale measurement experiment of a concrete test piece intended for foundation pile was conducted. Also, in order to make this influence less effective, Langevin transducer was used instead of the AE transducer for inputting ultrasonic wave with stronger amplitude and average response method was applied before analyzing the waveform with cepstrum analysis. It was thought that, by using a stronger input from Langevine transducer instead of the input from AE transducer, better SN ratio would be achieved. [1-4)] As a result of the experiment, it was confirmed that the clarity of the detection of a reflection wave improved by using Langevine transducer as its input and applying average response method before performing cepstrum analysis. As the result, the length of the concrete test block was estimated at 893 mm, and the error was 7 mm.

2. EXPERIMENT

(1) Experimental Setup

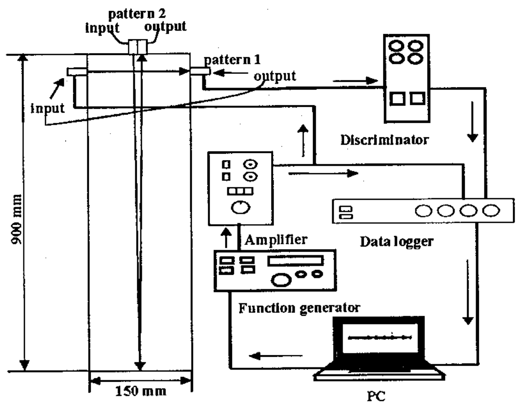

Fig.2 Experimental Setup

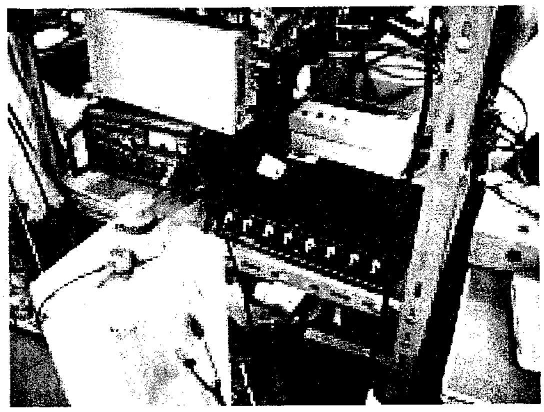

Fig.3 Picture of Experimental Setup

Fig.2 shows the schematic of the experimental setup. In this study, a concrete test piece with 120 mm square and 900 mm major axis was used. The main objective of this study was to obtain the actual length of the major axis. In construction sites, foundation piles with major axis length of over 10 to 20m are used. It is thought that this method can be applied to smaller piles with major axis length, maximum of 5m regarding its input strength and the ultrasonic wave attenuation. First, the minor axis, which was intended as the part of the foundation pile that shows up above the ground in the real situation, was measured using the ultrasonic wave measuring method. It is a simple method where the time it takes for the ultrasonic wave to move through a specific object with an already known length is used to calculate the velocity of the ultrasonic wave. It can be assumed that, the minor axis will not always be above the ground for measurement in which case, conventional velocity of ultrasonic wave in concrete will be used. The two sensors measurement method in this study is mainly intended for foundation pile with some of its part showing above ground however, it can be applied in different situations.

The ultrasonic wave measuring method was carried out using transducers set as shown in Fig.2(pattern 1). Using the minor axis, which is attached on both sides facing each other, the experiment was carried out. These transducers were attached with electron wax. Then, the transducers were attached as shown in Fig.2(pattern 2) in order to measure the length of the test piece. In this experiment, the length of the major axis, which was 900 mm was regarded as the penetration length of the boulder. The transducers in pattern 2 were also attached with electron wax. The purpose of this measurement was to obtain the reflection wave. If the arrival time of the reflection wave and the velocity of the ultrasonic wave of the test specimen are identified, it is possible to estimate the size of the specimen. Therefore, if it is possible to obtain a clear reflection wave, the result of this procedure will be more precise. In these experiments, two transducers were used as shown in Fig.4.

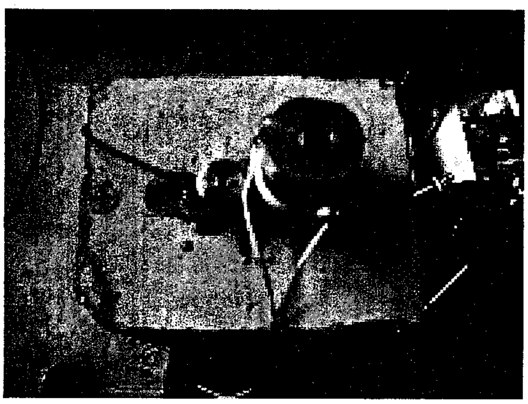

Fig.4 Ultrasonic Transducers Setup

Langevine transducer with resonance frequency of 40kHz was used as input and AE transducer with resonance frequency of 50kHz was used as output. Both transducers were made by Fuji Ceramics Corporation. Model number of the Langevine transducer was FBL40452HS and model number of the AE transducer was AE503S. Langevine transducer was a strong vibration producer only intended for outputting a wave that has a frequency of 40kHz therefore, only the frequency characteristic of the AE transducer is shown below in Fig.5. By observing Fig.5, it can be seen that this AE transducer has a resonance frequency around 50kHz and steadily declines its resonance as the level of frequency ascends.

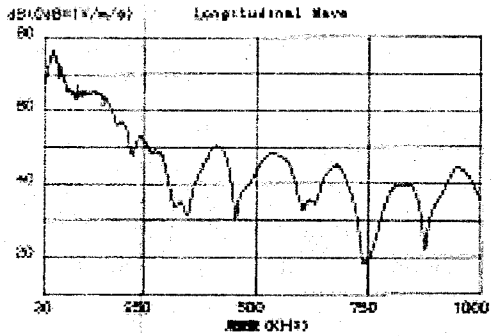

Fig.5 Frequency Response of AE Transducer

For the input vibration, burst wave signal with frequency of 40kHz was used. The function generator created this wave signal. Then this wave signal was transmitted to the amplifier to amplify its amplitude. The maximum output voltage of the amplifier was $150V_{p-p}$. Input voltages from the amplifier were stored into the data logger. The ultrasonic burst wave was inputted into the concrete test piece via the Langevin transducer. Then, the output signal was picked by the receiver AE transducer and was transmitted to the data logger. The sampling frequency of the data logger was 1 MHz.

(2) Ultrasonic Velocity Measurement Inside Concrete Block

In this chapter, the result of measuring the velocity of the ultrasonic wave penetrating through the concrete test block is shown. The former waveform in Fig.6 shows the voltage wave that was induced into the generator Langevin transducer using a bipolar amplifier, and the latter waveform in Fig.6 shows the output wave received by the receiver AE transducer.

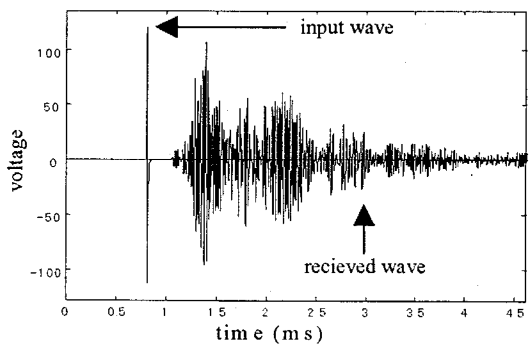

Fig.6 Ultrasonic Velocity Measurement

This time, the major axis of the concrete was measured which was 900mm long with sensors set on two ends, oppositely facing each other. When this maneuver is carried out on foundation piles already buried, this will not be the case because the major axis will not be measured directly. Although there was only a minute difference between ultrasonic velocity estimated from the major axis and ultrasonic velocity estimated from the minor axis, the former was used for better result in this experiment. Ultrasonic wave velocity was obtained by comparing the starting points of the waves in Fig. 6 by determining the time difference and dividing that value from the length of the known axis. The time difference was obtained by setting the threshold value as 1V, because the noise level was ± 0.5V. As a result, the time difference was obtained as 252 μ s, and the velocity of the ultrasonic wave of about 3571 m/s was obtained by dividing the time obtained with the length between the two transducers. This ultrasonic wave velocity was used in the analysis throughout this study.

(3) Behavior of the ultrasonic waves inside the concrete test piece

When transmitter Langevin transducer and receiver AE transducer are set to the concrete test piece as shown in Fig.4, dilation wave is transmitted into the concrete test piece. Here, it can be assumed that the receiver AE transducer will receive two kinds of waves. One is the direct wave, which comes in from the Langevin transmitter aligned right next to receiver AE transducer via the surface of the concrete. The other is the reflection wave, which propagates through the concrete and reflects back to its source. The two sensors are set close to each other in order to receive surface wave as a dilation wave instead of the volume change wave. This way, it can be regarded that the direct wave and the reflection wave have the same characteristics, as both waves are dilation waves. The assumed propagation patterns of ultrasonic waves inside the concrete test block are being shown in Fig.7.

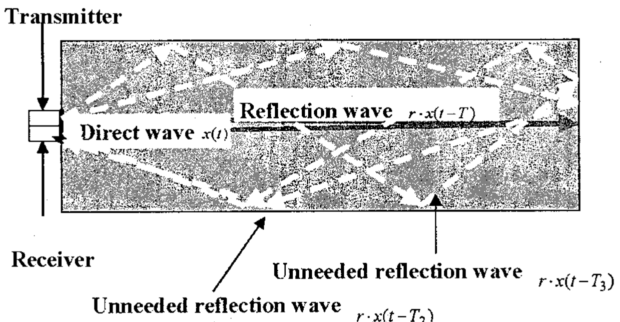

Fig.7 Ultrasonic Waves Inside Concrete

Here, the projected equation of the direct wave and the reflection waves is discussed. First the direct wave propagating on the surface of the concrete test block can be written as $x(t)$. When the reflection coefficient is constant despite its frequency, the decreasing rate of $x(t)$ is expressed as r and the time lag of $x(t)$ is expressed as T. By using these coefficients, the reflection wave can be expressed as $r\cdot x(t-T)$. Also, when the receiver AE transducer receives an array of reflection waves, this system can be thought as an impulse response system, shown in Eq.(1).

$$g(t)=\delta(t)+r\cdot\delta(t-T) \qquad (1)$$

$\delta(t)$:impulse

$g(t)$:impulse response from the system

Variable $y(t)$ can be considered as the output of this system when signal $x(t)$ is inputted into this system. Therefore, convolution equation can be written.

(4) Experiment of receiving the reflection wave

Input waveform was directly given using the function generator and the output waveform was given the receiver AE transducer. The vertical axis indicates voltage (V) and the horizontal axis, time (ms). Burst wave with frequency of 40kHz was used as its input and out put wave was received with receiver AE transducer. However, reflection wave could not be distinguished because the Langevin ceramics vibrate violently and it could not be easily damped. In this paper, the frequency of input signal was set to 40kHz, because improvement of measuring accuracy was aimed by making frequency high. Also, separation of a direct wave and a reflection wave was tried by shifting the frequency of an input signal a little from the resonance frequency of AE transducer[1]. If this output waveform included the reflection wave, the arrival time of the reflection wave was obtained using cepstrum analysis.

3. CEPSTRUM ANALYSIS

(1) Basic Theory of Cepstrum Analysis

Cepstrum analysis is a way to separate and analyze the signals when several signals are add up to form a convolution equation[5].

According to the explanation given in chapter 2, (3), variable $y(t)$ can be considered as the output of this system when signal is inputted into this system. Therefore, convolution equation can be written as Eq. (2).

$$y(t)=x(t)*g(t) \qquad (2)$$

First step of the cepstrum analysis is to apply the FFT analysis to change the equation to frequency spectrum. Here, the convolution process becomes a simple multiplication. The frequency spectrum of $y(t)$, $x(t)$, $g(t)$ are $Y(\omega)$, $X(t)$, and $G(\omega)$. The equation becomes as shown in Eq. (3).

$$Y(\omega)=X(\omega)\cdot G(\omega) \qquad (3)$$

Next, logarithm is taken from frequency spectrum equation in order to separate the two variables as shown in Eq. (4).

$$\log|Y(\omega)|^2=\log|X(\omega)|^2+\log|G(\omega)|^2 \qquad (4)$$

Finally, the equation is transformed using the IFFT to extract the frequency components of the constant ripple seen throughout the spectrum figure. Fig.8 shows the flow diagram of the cepstrum analysis.

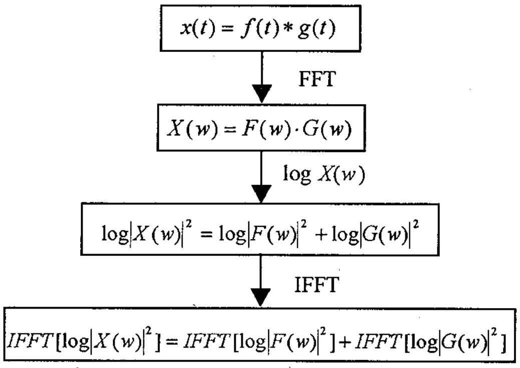

Fig.8 Cepstrum Analysis Flow Chart

(2) Reflection wave detection using Cepstrum Analysis

When there is a reflection wave included in the received wave, periodic ripple appears in the power spectrum. Here, to make it easy to understand, an equation that contains a single reflection wave is shown below in Eq.(5).

$$y(t) = x(t) + r \cdot x(t-T) \quad (5)$$

Next the frequency spectrum of the equation above is showed in Eq.(6).

$$Y(e^{j\omega}) = X(e^{j\omega})(1 + re^{-jT\omega}) \quad (6)$$

Here, cosine wave type of periodic ripple can be observed. The next equation shown in Eq.(7) is the equation where the logarithm was taken from the previous Eq.(6).

$$\hat{y}e^{j\omega} = \log X(e^{j\omega}) + \log(1 + re^{-jT\omega}) \quad (7)$$

Equation can be expanded as below in Eq.(8) using the Maclaurin expansion.

$$\log(1 + re^{-jT\omega}) = \sum_{m=1}^{\infty} \frac{(-1)^{m+1}}{m}(re^{-jT\omega})^m$$

$$0 < r < 1$$

$$\hat{x}e^{j\omega} = \log X(e^{j\omega}) + re^{-jT\omega} - \frac{r^2}{2}e^{-j2T\omega} + \frac{r^3}{3}e^{-j3T\omega} - \cdots$$

$$\hat{x}e^{j\omega} = \log\left[X(e^{j\omega})re^{-jT\omega}(1 + \frac{1}{r}e^{jT\omega})\right] \quad (8)$$

As shown in the equation above, it becomes an equation that contains infinite harmonic components when the ripple undergoes non-linear logarithm conversion. Eq. (9) shows the result when IFFT was applied to Eq.(8).

$$\hat{y}(t) = \hat{x}(t) + r\delta(t-T) - \frac{r^2}{2}\delta(t-2T) + \frac{r^3}{3}\delta(t-3T) - \cdots \quad (9)$$

As shown above in Eq.(9), sharp peaks appear on the arrival time of the reflection wave and the multiple of T . The existence of the reflection wave, its arrival time T , and its attenuation constant r can be estimated from the appearance of the sharp peak.

(3) Difficulties Using the Cepstrum Analysis

Cepstrum analysis is a very effective way to detect the reflection wave, which has the same frequency characteristics as the direct wave. It gives us an acute peak when it detects a reflecton wave. However, cepstrum analysis also has vulnerability of its own.

Fig.9 and 10 each shows the results during the cepstrum analysis being applied to the data during its process.

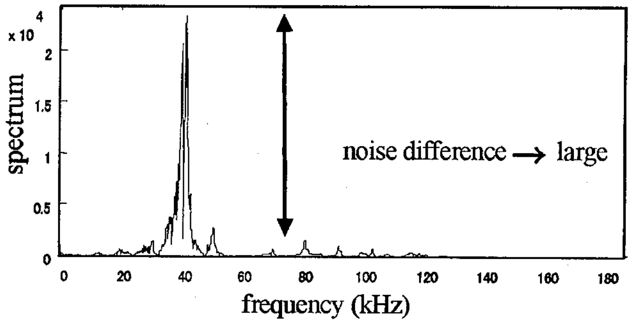

Fig.9 Frequency Spectrum of Output Wave

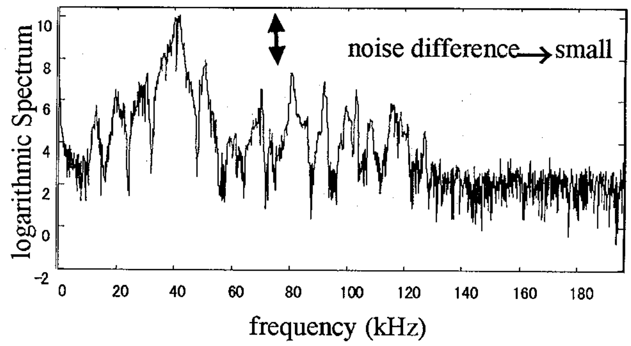

Fig.10 Logarithm Taken from Frequency Spectrum of Output Wave

Fig.9 shows the result during the cepstrum analysis when FFT was performed on the data. It can be observed that the difference between the needed data and the noise data is big in this case. Fig.10 shows the result during the cepstrum analysis when logarithm was taken after FFT was performed to the data. It can be observed that the difference between the needed data and the noise data is relatively very small here. Thus showing that cepstrum analysis is vulnerable to relatively small noise.

(4) Computer Simulation

In this section, the result of a computer simulation is shown, which was carried out to test the effectiveness of the cepstrum analysis. The main purpose here was to conduct a test to see how the result of the cepstrum analysis varies with different degree of noise added to the generated waveform. This simulation was carried out using MATLAB.

First of all, in order to generate a waveform imitating the result obtained from actual ultrasonic wave measuring method, a waveform with frequency component of 40kHz, steadily declining its amplitude was generated. Then, as the reflection wave, waveform with its frequency component of 40kHz and 0.077 times smaller in size was added at 2ms. The rate of decrease was decided according to the experiment done in section 1 on this chapter. This generated waveform is shown in Fig.11.

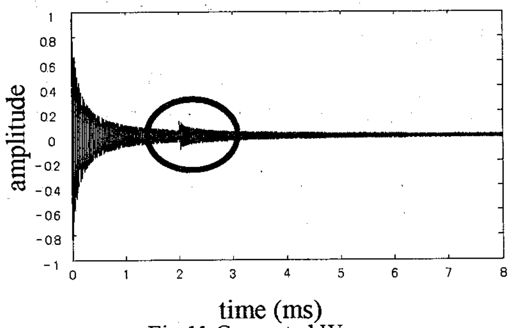

Fig.11 Generated Wave

Next, in order to imitate the actual result obtained from the experiment, noise waveform with standard deviation of 1 was created arbitrarily. This noise waveform is shown below in Fig.12. As it can be seen below, no pattern exists in the noise waveform that was created.

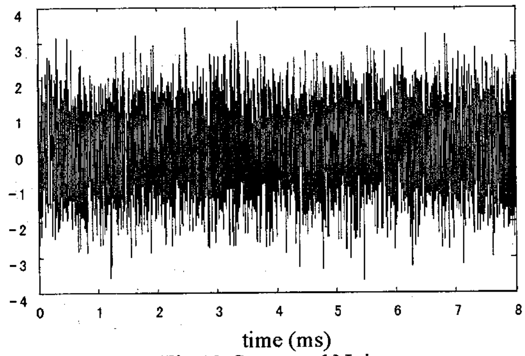

Fig.12 Generated Noise

This noise wave form was varied its size by simply multiplying and added to the waveform shown in Fig.11 in order to generate a model wave from with arbitrary sn ratio. As the result, next two graphs were successfully generated. Fig. 13 shows a waveform with its SN ratio at 20 and Fig.14 shows a waveform with its SN ratio at 40.

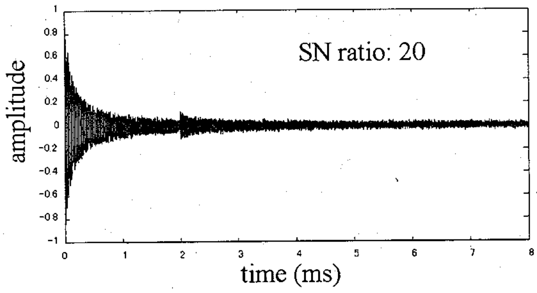

Fig.13 Generated Wave with Noise Ratio of 20

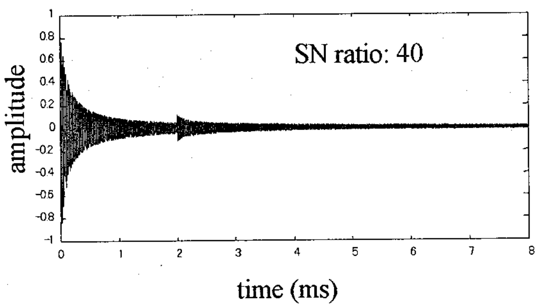

Fig.14 Generated Wave with Noise Ratio of 40

By comparing Fig.13 and Fig 14, it can be observed that the former contains clearly recognizable noise on the surface of its waveform.

Finally, cepstrum analysis was conducted on the generated waveforms to see whether it will detect the reflection wave or not. Fig.15 and 16 show these results.

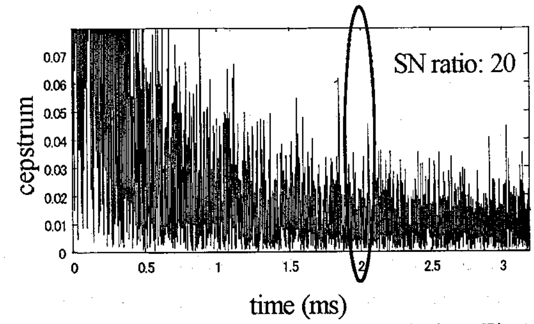

Fig.15 Result of Applying Cepstrum Analysis to Fig.13

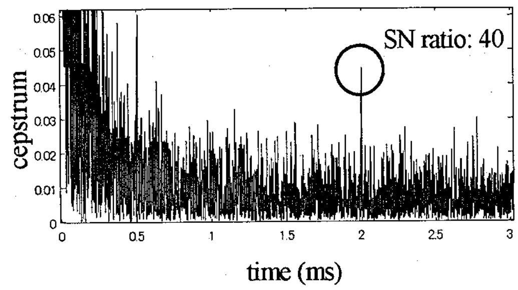

Fig.16 Result of Applying Cepstrum Analysis to Fig.14

From Fig.15, it can be said that, cepstrum analysis is useful to analyze a waveform that has an SN ratio of 40. From Fig.15, it can be said that, cepstrum analysis is not useful to analyze a waveform that has an SN ratio of 20.

From these results, it can be concluded, when the waveform obtained as the result of this experiment have an SN ratio that is close to 40 or higher, optimum result will be obtained.

(5) Result of Detecting the Depth of Foundation Pile Using Cepstrum

In our previous research, AE transducer was used to input ultrasonic wave to subject. However, the obtained result contained high degree of noise. Therefore, the results varied when cepstrum analysis was used to obtain the arrival time of the reflection time. This was because cepstrum analysis was vulnerable to noise. In order to solve this problem, authors have used Langevine transducer as an input for stronger amplification and to make the noise less effective.

Here the results are shown when Langevin transducer with resonance frequency of 40kHz was used as the transmitter and AE transducer resonance frequency of 50kHz was used at the receiving end. Fig.17 shows the result obtained by the receiver AE transducer when burst waveform with frequency component of 40kHz was inputted into the concrete test piece.

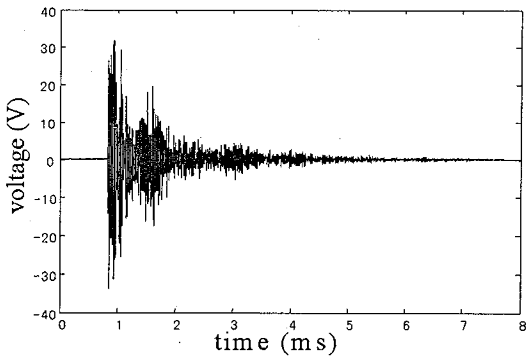

Fig.17 Obtained Waveform

As a result of using a Langevin transducer as input, the output wave had strong amplitude compared to the case when an AE transducer was used as input[1-4) however, the waveform in Fig.17 clearly contains a large amount of noise and it had a SN ratio of 12.88. By applying cepstrum analysis to Fig.17, Fig.18 shown below was obtained however; in this case reflection wave was unrecognizable.

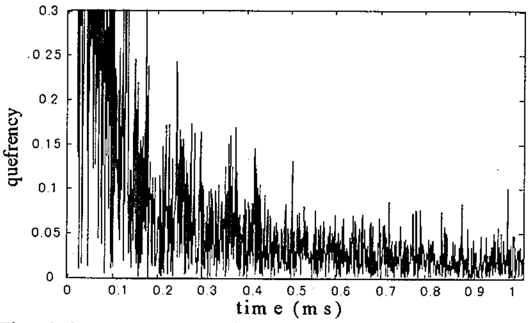

Fig.18 Cepstrum Analysis Applied to the Obtained Waveform

In order to make the effect of the noise less, average response method was applied to the waveform above. The equation of the average response method is expressed as Eq.(10).

$$\bar{y}_M(n) = o(n) + \frac{1}{M}\sum_{j=0}^{M-1} v_j(n) \qquad (10)$$

where,

M:the number of samples

v_j:the noise of j th data

Average response method is a simple noise filtering method used by assuming that the data taken from repeatable source contains a main data, which is always consistent and noise data, which always comes out differently. Therefore the noise is canceled out when the data taken from repeatable source is added up and the wanted signal builds up. Bigger the number of data added, better the result. In this experiment, 10 data were added in order to obtain Fig.19.

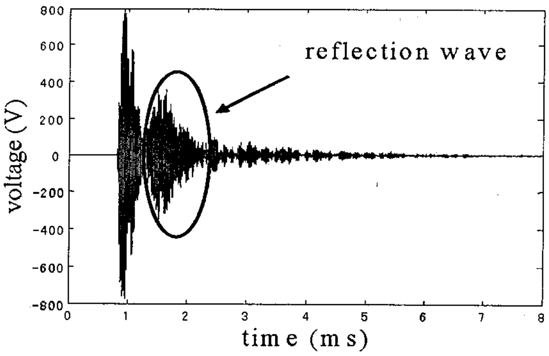

Fig.19 Average Response Method Applied to Obtained Waveform

Here the effect of noise is greatly reduced and the reflection wave is clearly recognizable. Fig.20 shows the result of after cepstrum analysis was performed on the waveform in Fig.19.

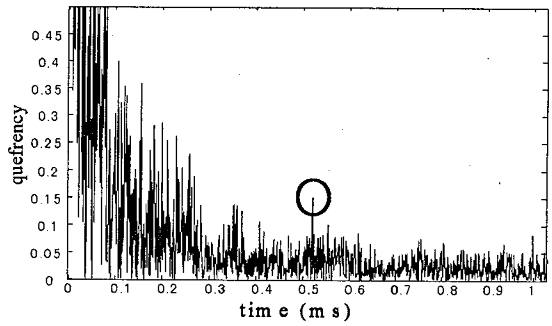

Fig.20 Cepstrum Analysis Applied to the Result of Average Response Method

In Fig.20, the cepstrum peak was confirmed at 0.5 ms. Therefore the arrival time of the reflection wave was confirmed at 0.5ms. Compared to previous results[1-4) with AE transducer as the input to the system, the cepstrum peak stands out by itself. By using this result, the length of the concrete test piece can be calculated as shown below in Eq.(11).

$$L \approx \frac{l_1 + l_2}{2} = \frac{V \times t}{2}$$

$$L = \frac{3571 \times 0.0005}{2} = 893[mm]$$

$$\text{error} = 900 - 893 = 7[mm] \qquad (11)$$

l_1 :length of the major axis of the concrete test piece which the ultrasonic wave propagates initially

l_2 :length of the major axis of the concrete test piece which the ultrasonic wave propagates after it has reflected from the bottom of the object

the length between the sensors are ignored because it is minimal compared to the major axis of the concrete test piece

As result, the length of the concrete test piece was estimated as 893mm. The actual length of the concrete test piece was 900mm therefore; the margin of error was 7mm. The accuracy of the measurement have improved mainly because in previous researches, the result of the cepstrum was greatly effected by noise, making it hard to distinguish the arrival time from the background noise.[1-4] In this research, the effect noise was reduced and the peak became distinguishable.

4. CONCLUSION

Authors have developed a system, still at the experimental stage that measures the depth of the concrete object with precise accuracy and repeatability. This technique can be applied for measuring length of foundation piles.

From this system, authors were able to obtain an output wave, which contains the wanted reflection wave mixed together with the unwanted direct wave. In this paper, emphasis was on separating the reflection wave from the mixed wave by using the cepstrum analysis. However it was not able to separate the direct wave and the reflection wave because the cepstrum analysis is vulnerable to noise and the data contained large degree of noise. By performing a computer simulation, it was able to define that; the SN ratio between data and noise must exceed 40 in order to obtain an ideal result.

In order to solve this problem, Langevine transducer was used as the input of the measurement system and average response method was used before performing the cepstrum analysis. As a result, the arrival time of the reflection wave was shown clearly on the peak of the cepstrum waveform. The length of the concrete test piece was calculated at 893 mm by using the arrival time of the reflection wave and the velocity of ultrasonic wave inside the concrete test piece. The actual length of the concrete test piece was 900mm therefore; the margin of error was 7mm. This is a precise value compared to the case when elastic impact wave method with hammer is used because of high resolvability of ultrasonic wave, compared to that of a hammer produced wave.

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