Evaluation of the Concrete Strength with the Quality Factor of Ultrasonic Signal

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Concrete is broadly employed in many kinds of constructions. Inspection of the strength of the concrete is important for the safety of constructions. Though ultrasound is broadly employed for non-destructive testing, if only the strength of the concrete decreases but there is no markedly crack or unevenness inside, the ultrasonic signals will show little difference. Considering propagating property of ultrasound should be related with the strength of the material, a method of evaluating the strength of the concrete by the quality factor of the resonant peak of ultrasound propagating inside the concrete is proposed. The linear predictive coefficient (LPC) processing method is introduced for calculating the quality factor from the ultrasonic signals. In the measurement, an electromagnetic induction (EMI) type sound source is employed for transmitting powerful broad-banded impulsive ultrasound into the concrete. Concrete specimen with varies strengths are measured by setting both the sound source and the receiver on a same surface of the concrete. All the receiving signals show complicated waveforms, and the differences among them are hard to be distinguished. However, the quality factors of the resonant peak of receiving signals derived by the LPC processing method show the tendency agrees well with that of the compressive strengths of corresponding concrete specimen. Moreover, the proper driving frequency of EMI sound source and resonant frequency of receiver for more stable quality factor is discussed in this paper.

1 Introduction

Concrete is a popular material employed broadly in many constructions, such as buildings, tunnels, bridges, and roads. Because the strength of concrete will decrease extend a long term of usage, the periodic inspection is extremely important for the safety of constructions. However, the inspecting method generally employed are “watching” the outlook and “listening” to the hammer-strike response of the concrete in current application. Problems of instability and low accuracy can be pointed out. The technique of inspecting the quality of the concrete easily and accurately is expected.

Though impact-echo method [1] is efficient for crack detection or background discrimination, it is necessary to receive high level ultrasonic waves reflected from the crack or unevenness inside the concrete, or from the interface of the concrete and its background medium. However, if the concrete varies only in strength, the time domain signals as well as their spectra will show little difference. Considering that the propagating properties of the ultrasonic wave should be related with the strength of the medium, a method of evaluating the strength of the concrete by the quality factor of the resonant peak of multi-reflected ultrasonic wave propagating inside the concrete is contrived [2].

An electromagnetic induction type (EMI) sound source, which is similar in structure as that has been successfully employed in underground imaging [3] but smaller in scale, is employed to radiate powerful impulsive ultrasonic wave into the concrete. An receiver consisting of a piezoelectric transducer placed on the surface of the concrete is employed to receive the ultrasonic wave (direct wave and multi-reflected waves) propagating inside the concrete. In order to acquire stable quality factor of the resonant peak, an all-poles model processing method, linear predictive coefficient (LPC) method [4] is employed for spectrum derivation and quality factor calculation.

Three concrete specimens differ in strengths are measured, with two kinds of driving frequencies employed for EMI sound source, respectively. Though the strengths can hardly be distinguished from the time domain signals, the spectra derived by LPC show a highest resonant peak near the resonant frequency of receiver, and the comparison results of different concrete specimen show that the tendency of the quality factors of resonant peak agrees well with that of the strengths of concrete. Moreover, the comparison results of different driving frequencies show that sharper resonant peak of spectra with higher and more stable quality factors can be derived while the driving frequency of sound source fits with the resonant frequency of receiver.

2 Method of Inspection

2.1 Measurement of ultrasonic waves

Figure 1 shows the diagram of measuring system. An EMI sound source and a receiver placed on the surface of the concrete specimen are employed to transmit and receive the ultrasonic waves propagating inside the concrete, respectively. The EMI sound source consists
of mainly a spiral coil cemented on Bakelite plate and an aluminium diaphragm under the coil. While the electrical energy charged in the condenser is instantaneously discharged to the spiral coil, eddy current is induced inside the aluminium diaphragm by the electromagnetic field radiated from the coil; therefore, driven by the impulsive electromagnetic inductive force, the aluminium diaphragm vibrates as a sound source.

The main driving frequency of the sound source is determined by the resonant frequency of the inductance of the coil and the capacity of the condenser. However, as the impulsive driving provides a broad frequency band, and the main resonant frequency of the measuring system should be that of the receiver, which is measured to be about 25 kHz.

In this paper, three concrete specimens, with identical dimension (15 cm × 15 cm × 52 cm), differing in strength (67.20, 39.23, and 21.15 N/mm², respectively) are measured, and two kinds of driving frequency are employed for studying the effectiveness of inspection with the quality factor of the resonant peak of ultrasonic wave propagating inside the concrete should vary with the strength. In order to acquire the spectra concentrating on the resonant peak and thus the stable quality factor, an all-poles model processing method, linear predictive coefficient (LPC) method, is employed for spectrum derivation and quality factor calculation.

The linear prediction can be described simply as the prediction of the present datum by the linear synthesis of the former data,

\[ x'_n = - \sum_{i=1}^{p} a_i x_{n-i} \quad (n = p + 1, p + 2, \ldots, N) \]  

where \( x'_n \) is the predictive value of present datum, \( a_i \) is the LPC, \( p \) is the order of prediction, and \( N \) is the data length. Regarding a known signal \( x_n \) \((m=1,2,\ldots,N)\), by introducing a prediction error \( e_n \) between the real value \( x_n \) and the predictive value \( x'_n \) as

\[ e_n = x_n - x'_n = x_n + \sum_{i=1}^{p} a_i x_{n-i} \quad (n = p + 1, p + 2, \ldots, N) \]

Then the LPC \( a_i \) can be derived by the least-square condition of the prediction error \( e_n \), which gives the simultaneous equations of \( a_i \) as

\[
\begin{bmatrix}
    R_0 & R_1 & \cdots & R_{p-1} \\
    R_1 & R_0 & \cdots & R_{p-2} \\
    \vdots & \vdots & \ddots & \vdots \\
    R_{p-1} & R_{p-2} & \cdots & R_0
\end{bmatrix}
\begin{bmatrix}
    a_1 \\
    a_2 \\
    \vdots \\
    a_p
\end{bmatrix}
= \begin{bmatrix}
    R_1 \\
    R_2 \\
    \vdots \\
    R_p
\end{bmatrix}
\]

where

\[ R_i = \frac{1}{N-p} \sum_{n=p+1}^{N} x_n x_{n-i} \quad (i = 1, 2, \ldots, p) \]

is the self-correlation of \( x_n \).

With \( a_i \), the spectrum of the signal can be expressed by Z-transform of Equation (1) as

\[ X(z) = \frac{1}{1 + \sum_{i=1}^{p} a_i \cdot z^{-i}} \]  

where \( z = e^{j\omega \tau} \) and \( \tau \) is the sampling interval.

By factorizing the denominator of Equation (2), i.e., assuming \( b_n \) and \( b_n^* \) \((n=1,2,\ldots,p/2)\) are the \( p/2 \) \( (p \) is even) pairs of complex conjugate roots, Equation (2) can be rewritten as

\[ X(z) = \frac{1}{(1-b_1 Z^{-1})(1-b_1^* Z^{-1}) \cdots (1-b_p Z^{-1})(1-b_p^* Z^{-1})} \]  

Obviously, Equation (3) shows an all-poles spectrum with \( p/2 \) peaks, because \( X(z) \) should be a pole whenever \( z=b_n \).

As to \( n \)-th pole, by substituting \( b_n = c_n e^{j\theta_n} \) \((c_n \) and \( \theta_n \) are the modulus and the argument of \( b_n \), respectively) and \( z = e^{j\omega \tau} \), the \( n \)-th factor of the denominator \( Y_n(z) \) can be represented as

\[ Y_n(z) = 1 - b_n Z^{-1} = 1 - c_n e^{j\theta_n} = 1 - c_n e^{j(\theta_n - \omega \tau)} = 1 - c_n \]  

\[ (c_n = 1) \]
Then the $n$-th resonant frequency $\omega_{0n}$ and its bandwidth $\Delta \omega_n$ can be drawn from the following conditions.

$$\arg \{ \gamma(z) \}_{\omega = \omega_{0n}} = 0 ; \quad \arg \{ \gamma(z) \}_{\omega = \omega_{0n} + \Delta \omega} = \frac{\pi}{4}$$

That gives

$$\omega_{0n} = \frac{\theta_n}{\tau} ; \quad \Delta \omega_n = \frac{1 - c_n}{\tau}$$

therefore, the quality factor of the $n$-th pole is

$$Q_n = \frac{\omega_{0n}}{2\Delta \omega_n} = \frac{\theta_n}{2(1 - c_n)}$$

The procedure of calculating the quality factor from original data is concluded in Figure 2. Moreover, the order of LPC $p=30$ is employed [2], in this paper.

3 Experimental Results

Figures 3(a)-3(c) show examples of the received signals measured with driving frequency of 100 kHz (C=0.5 $\mu$F), from three concrete specimens with different strength, respectively. Those measured with driving frequency of 25 kHz (C=8 $\mu$F) are shown in Figure 4. Because all the direct wave and multi-reflected waves propagating in the concrete along multi-paths are received with interference between each other, all the signals in Figures 3 and 4 show complicated waveforms, and the rule in time domain signals corresponding to different concrete specimen can hardly be drawn.

Correspondingly, Figures 5 and 6 show the normalized spectra, derived by the LPC, of the signals shown in Figures 3 and 4, respectively. Comparatively, the spectra shown in Figure 5 derived from higher driving frequency show much higher frequency components, than those shown in Figure 6. While those in Figure 6 show narrower bandwidth and sharper resonant peak around 25 kHz, owing to that the driving frequency matches the resonant peak.

On the other hand, all the spectra in both of the figures show a highest peak near the resonant frequency of the receiver, which indicates best SNR than other poles derived by LPC processing. Therefore, in this paper, the quality factor of the pole near the resonant frequency of receiver is employed to evaluate the strength of the concrete.
Figure 4: Example signals measured with driving frequency of 25 kHz

The quality factors of resonant peak derived by LPC analyzing method are noted in every corresponding spectrum shown in Figures 5 and 6. In both of the results, the comparison of the quality factors of different specimen indicates that the quality factors take same tendency with the corresponding strength of concrete specimen, though those in Figure 6 show higher values due to sharper resonant peak brought forth by the resonance of driving frequency.

Moreover, in order to verify the stability of the quality factor of resonant peak derived from multi-reflected ultrasonic waves measured by using different driving frequency, the distribution of quality factors derived from 10 measurements, on each specimen with each driving frequency, are concluded in Figure 7. The results show similar tendency as that can be drawn from the comparison results of Figures 5 and 6, i.e., the quality factors of different specimen take same tendency with the corresponding strength, while those derived from signals measured by using resonant driving frequency show higher values. Additionally, the comparison of distributions of the quality factors shows that the quality factors derived from signals measured by using resonant driving frequency are more stable, this indicates that a higher SNR at the resonant peak can be expected by using the resonant driving frequency.

Figure 5: Spectra of signals measured with driving frequency of 100 kHz

4 Conclusion

Method of evaluating the strength of the concrete with the quality factor of the resonant peak of multi-reflected ultrasonic waves propagating inside the concrete is studied. Electromagnetic induction type sound source is employed for irradiating impulsive ultrasound, and the linear predictive coefficient processing method is employed for calculating the quality factor of resonant peak. Three kinds of concrete specimen with different strengths are measured, with two kinds of driving frequencies.
In both cases, the time domain signals show complicated waveforms owing to the interference of the multi-path reflected pulses, and the strength of different concrete specimen is hard to be distinguished, while the quality factors of resonant peak of the ultrasonic waves derived by linear predictive coefficient analysis show the tendency agrees well with that of the strengths of corresponding concrete specimen. Moreover, sharper resonant peak and higher quality factor can be derived from the signals measured by using resonant driving frequency, and the quality factors of several measurements are more stable. Hence, using the resonant driving frequency is more efficient for evaluating the concrete strength by the proposed method.

References


