DEVELOPMENT OF ACTIVE SENSING-BASED REAL-TIME CONCRETE STRENGTH ESTIMATION MODEL

D.-J. Kim[1], C. Lee[2], S. Park[2]*
[1] Department of u-City Design & Engineering, Sungkyunkwan Univ., Suwon, Korea
[2] Department of Civil & Environmental Engineering, Sungkyunkwan Univ., Suwon, Korea
* Corresponding author (shparkpc@skku.edu)

Keywords: *concrete strength monitoring, embedded PZT sensor, impedance, guided-waves, linear regression*

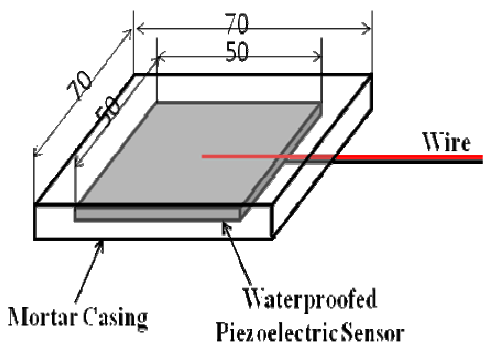
1 Introduction

Recently, there has been increasing demand for super high-rise buildings or super long span bridges. This means there is a need for large amounts of concrete structures in civil environments. On the other hand, concrete structures might be susceptible to brittle fracture if their curing process is inadequate. Therefore, to prevent this problem, it is essential to predict the absolute strength of the concrete material nondestructively. In addition, continuous monitoring of the strength is important for reducing the construction time and cost because it can determine the appropriate curing time to achieve sufficient strength to progress to the next phase safely. Conventionally, the in-situ strength of concrete structures can be determined with high precision by performing strength testing and material analysis on core samples removed from the structure but this method should destroy the concrete structure itself [1]. Therefore, a range of methods based on the thermal, acoustical, electrical, magnetic, optical, radiographic and mechanical properties of the test materials have been developed to monitor the strength development without damaging the host structure [2-4]. These methods typically measure certain material properties of concrete from which the strength and/or elastic constants can be estimated. Among these techniques, methods using a Schmidt hammer or integrated temperature are used widely. Nevertheless, they are unsuitable for use at construction sites because they do not allow real-time monitoring of the curing process of concrete structures at inaccessible places. Therefore, this study proposes a new concept of real-time strength monitoring technique based on piezoelectric materials. Electromechanical impedance techniques that employ piezoelectric materials have emerged as a potential tool for the implementation of a built-in monitoring system for civil infrastructures [5-8]. This technique utilizes high-frequency structural excitation, which is typically > 20 kHz from surface-bonded PZT(lead zirconate titanate) patches, to sensitively monitor the changes in the mechanical impedance of the test structures [9]. In addition, the guided-wave method using a piezoelectric sensor was used to detect structural damage [10]. In this study, efforts to confirm the applicability of the electromechanical impedance and guided-wave using embedded piezoelectric sensor have focused monitoring on the strength of concrete structures.

2 Active sensing-based concrete stregth estimation

2.1 Manufacturing of embedded PZT sensor

To monitor internal strength of concrete structures, the PZT patches need to embed to concrete. The bare PZT patches cannot against to the impact and/or other environmental variation, the PZT has to be protected. To embed into the concrete structure, the embedded PZT sensor was manufactured as shown in Fig. 1. To protect from outside impact and internal transform, the mortar cover the waterproof coated PZT [11].



(a) Diagram of embedded PZT sensor

(b) Embedded PZT sensor Proto-type

Fig.1 Embedded PZT sensor

2.2 Self-sensing based active sensing measurement

Two waveforms were used to excite the host concrete structures. One was the linear chirp signal for the impedance measurements. Eq. (1) describes the linear chirp signal, which consists of sinusoidal waves with a frequency range.

$$x(t) = A \times \sin\left\{ t\left(\omega_0 + \frac{\omega_1 - \omega_0}{2N} t \right) \right\} \quad (1)$$

where A, ω_0, ω_1 and N are the amplitude, starting frequency, end frequency and number of samples, respectively.

The other one is the Morlet wavelet-based tone-burst signal for the guided-wave measurements, as shown in Eq. (2).

$$x(t) = A \times \exp\left\{ -\left(\frac{\omega t}{p} \right)^2 \frac{1}{2} \right\} \times \cos(\omega t) \quad (2)$$

where A, ω and p are the amplitude, driving angular frequency and number of peaks, respectively.

Recently, Lee et al proposed a self-sensing based measurement system [12]. A simple voltage divider composed of a reference capacitor was used to construct a self-sensing circuit, as shown in Fig. 2. In the previous study, the system was used only for one technique, the impedance or guided-wave method. In the present study, the circuit was applied

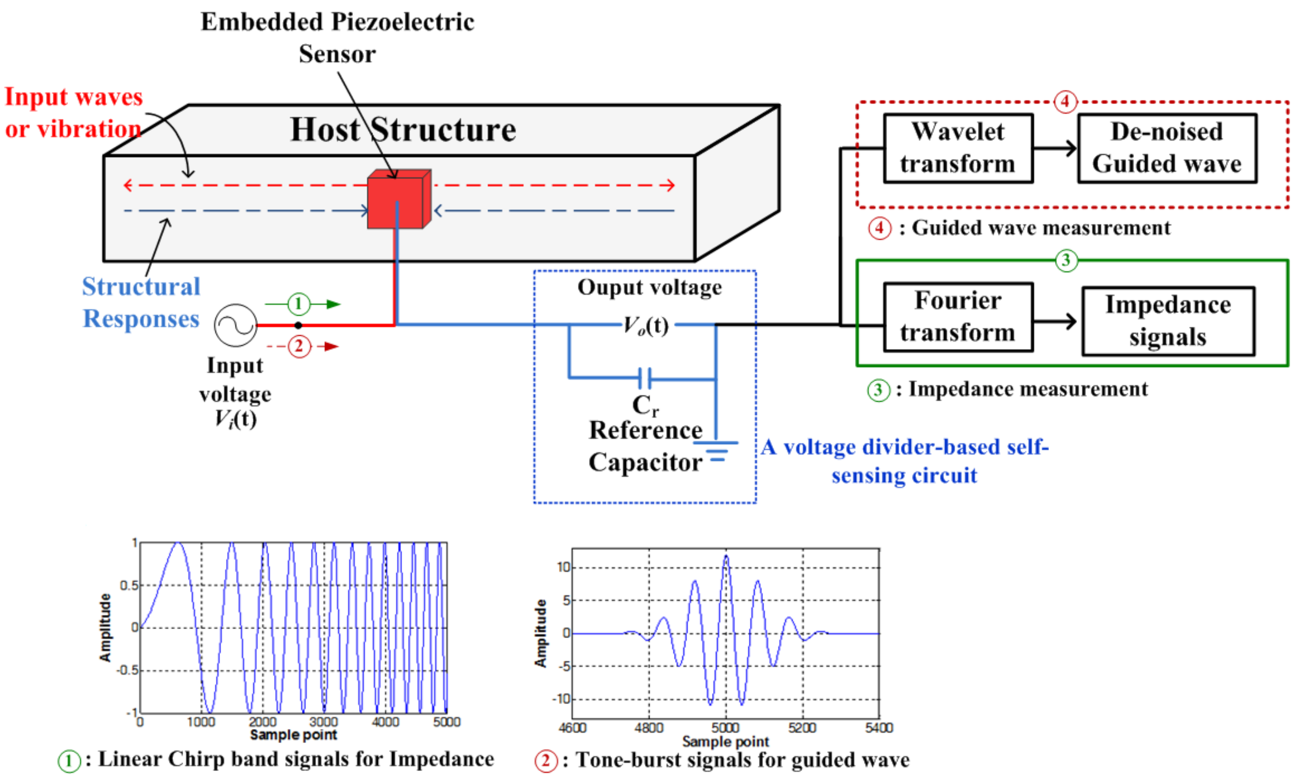


Fig. 2 Overview o f multi-scale actuated sensing based on the self-sensing scheme

to two methods simultaneously with different input waveforms

2.3 Multi-scale strength estimation method

The impedance and guided-wave signal represent the mechanical properties of host structure. The mechanical properties change is caused by the variation of strength dominantly in curing process. Therefore these signals vary according to strength variation of host concrete structure. The resonant frequency of impedance and amplitude of guided-wave are extracted as active sensing features because these features can represent the variation of each signal. Then the strength estimation model is established using linear regression method that finds the relationship between each active sensing feature and strength. To increase accuracy and reliability, multi-scale signal based strength estimation method is developed. The multi-scale based strength estimation method is established using two active sensing features simultaneously in linear regression. It can represent impedance and guided-wave in one strength model and each active sensing feature can compensate the other feature.

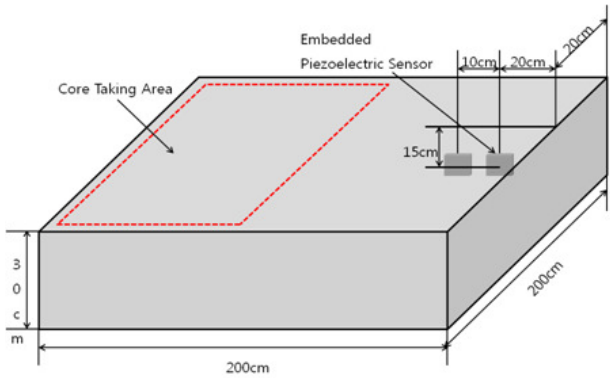
3 Experimental verification

3.1 Experimental setup

An experimental study using a plain concrete structure was carried out under an air curing process. The embedded piezoelectric sensor was buried in the edge of the concrete structure, and the remaining parts were used to extract the core to measure the compressive strength, as shown in Fig. 3. The embedded piezoelectric sensor was placed vertically to avoid moisture gathering below the sensor.

The experimental setup for the self-sensing impedance and guided-wave measurement system consisted of a self-sensing circuit board with a 20nF reference capacitor and a DAQ system (PXI 1042Q, National Instruments Inc.). The DAQ system consisted of an Arbitrary Waveform Generator (AWG), a Digitizer (DIG), embedded controller and data acquisition software (LabVIEW).

The frequency ranges of impedance measurement was determined to be 30 ~ 40 kHz because the resonant frequencies could be observed clearly in that range. The frequency of the input tone-burst



(a) Scheme of test specimen

(b) Picture of test specimen

Fig. 3 Test specimen

signal for guided-wave measurement was 80 kHz. To compare with the compressive strength, the core was extracted from the concrete structure and the compressive strength of the core was measured using a UTM(Universal Test Machine). The tests were performed at 2, 3, 5, 7, 10, 14 and 28 days because the concrete structure had insufficient strength to take the core before the 2nd day.

3.2 Active-sensing signature variations according to curing age

Fig. 4 shows the impedance measurements. Although the impedance peaks were not clear because the damping of concrete was high in this specimen, the resonant frequency shifted gradually to the right side with increasing strength development of the concrete due to increasing curing age.

Also Fig. 5 shows the result from the guided-wave measurement. Because the input signal was related directly to the output signal in the self-sensing based

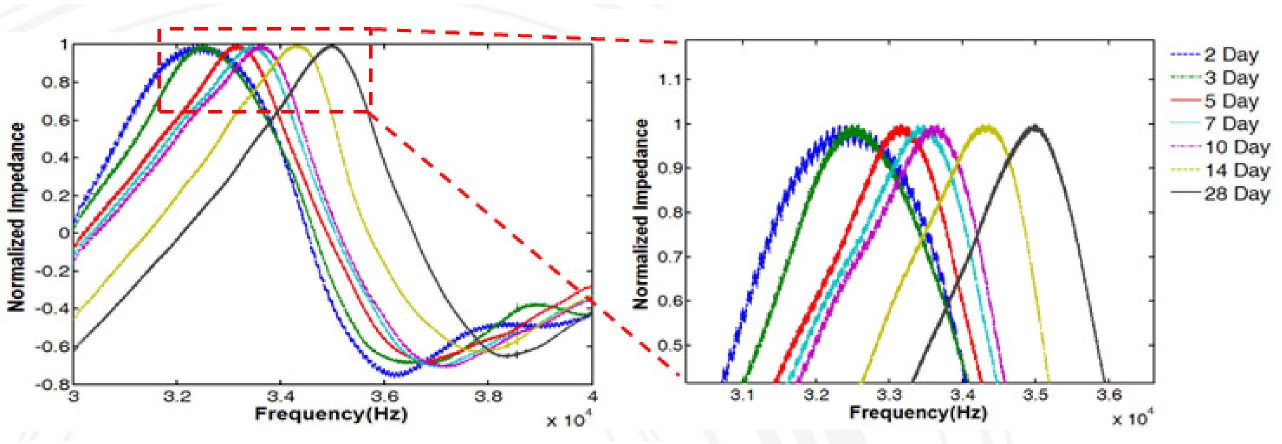


Fig. 4 Result of impedance measurement

guided-wave measurement method, the second wave packet that appeared next to the input signal was traced. The highest amplitude of the wave packet gradually increased with increasing curing age. This was caused by the increased stiffness of the test specimen during the curing process.

To estimate the concrete strength, the resonant frequency of the impedance and the maximum propagation amplitude of the wave were calculated as a feature. As shown in Table 1, the compressive strength of the extracted core was also measured for comparison. The relationships between the measured compressive strength and extracted features were derived using a linear regression method.

Table 1. Measured Compressive Strength

Curing Age (day)	2	3	5	7	10	14	28
Strength (MPa)	12.08	18.09	22.71	24.34	27.47	27.71	29.17

3.3 Multi-scale strength estimation model

The multi-scale based strength estimation model, as shown in Eq.(3), was derived from the linear regression analysis between the actual core compressive strength and the active sensing features: the resonant frequency of the impedances and the maximum amplitude of the guided waves.

$$S(MPa) = -6.178 R_I (kHz) + 203.8 A_W + 190.9 \quad (3)$$
$$R^2 = 0.9822$$

where S represents the real compressive strength of the core (MPa), R_I represents the resonant frequency of the impedance (kHz), and the A_W presents the amplitude of the guided-wave.

The proposed multi-scale strength estimation model is displayed in Fig. 6. To verify proposed multi-scale strength estimation model, the estimation strength was calculated using strength features of other curing ages.

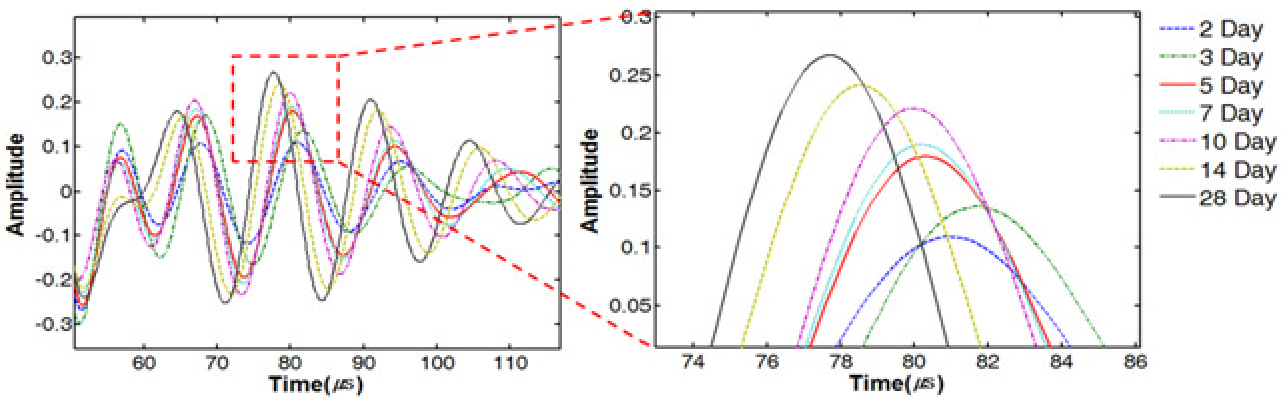


Fig. 5 Result of guided-wave measurement

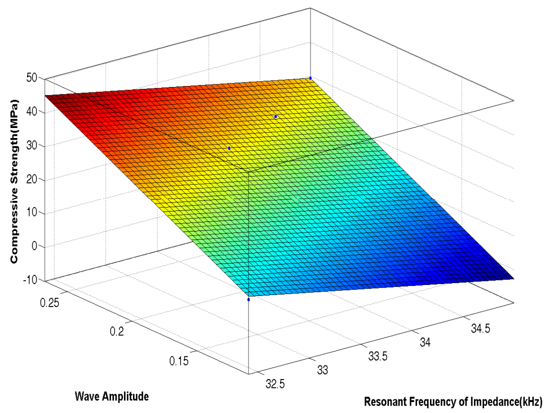


Fig. 6 Multi-scale based strength estimation model

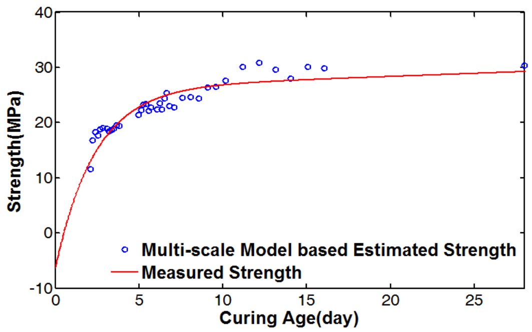


Fig. 7 Multi-scale based strength estimation model

Fig.7 shows the correlation between estimated strength and core tested strength. The errors was not bigger than ±10%. Therefore, by using the proposed model, the concrete strength can be estimated very easily in the construction sites in real-time.

4 Conclusion

This study proposed a active sensing-based real-time strength monitoring technique. To estimate the absolute strength of concrete continuously during its curing process, the impedance and guided-wave methods, which are normally used to detect structural damage nondestructively, was applied. The extracted active-sensing features were the resonant frequency of the impedance and the maximum propagation amplitude of the guided-wave signals. A linear regression method was used to confirm the relationship between the extracted active-sensing features of the signals and the strength of concrete. The experimental results showed that the resonant frequencies in the impedance signals shifted gradually to the right and the maximum propagation amplitude of the guided-wave were increased due to the strength development of the concrete. In addition, the resonant frequency of the impedance signals and the maximum propagation amplitude variation of the guided wave signals increased linearly with increasing strength development. To augment the accuracy of the strength estimation, a multi-scale model using both active-sensing features was also proposed. The multi-scale strength estimation formula showed an accuracy of 98%. Overall, the multi-scale strength estimation method using the embedded piezoelectric sensor can be used effectively to obtain the absolute strength of the concrete structures.

Acknowedgement

This study was supported by the u-City Master and Doctor Support Project funded by Ministry of Land, Transport and Maritime Affairs (MLTM), the Nuclear Research & Development of the Korea Institute of Energy Technology Evaluation and Planning (KETEP) grant funded by the Korea government Ministry of Knowledge Economy in Korea(20101610004J) and National Nuclear R&D Program through the National Research Foundation of Korea(NRF) funded by the Ministry of Education, Science and Technology (2010-0025889). This all-out support is greatly appreciated.

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