

저비용 음압센서를 이용한 콘크리트 구조물에서의 비접촉 Impact-Echo 기반 손상 탐지

Non-contact Impact-Echo Based Detection of Damages in Concrete Slabs Using Low Cost Air Pressure Sensors

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Abstract

The feasibility of using low cost, unpowered, unshielded dynamic microphones is investigated for cost effective contactless sensing of impact-echo signals in concrete structures. Impact-echo tests on a delaminated concrete slab specimen were conducted and the results were used to assess the damage detection capability of the low cost system. Results showed that the dynamic microphone successfully captured impact-echo signals with a contactless manner and the delaminations in concrete structures were clearly detected as good as expensive high-end air pressure sensor based non-contact impact-echo testing.

Keywords : Impact-echo, Contactless sensing, Low cost air pressure sensor, Dynamic microphone

1. Introduction

The impact-echo (IE) method is a mechanical wave-based NDT technique widely used in civil engineering field. A conventional IE testing setup consists of a contact type sensor, impact source (generally a steel ball is used), and data acquisition/processing/storage system (Malhotra and Carino, 2004). A working principle of IE testing for concrete is as follows. When a steel ball applies (e.g. an impact event) on the surface of a tested concrete, transient waves are generated in the concrete. The resulting transient surface motion, which is set up by a vibration resonance through the thickness of the element (thickness stretch mode), is detected by a contact sensor mounted on the surface. The obtained time domain signal is then transformed to frequency domain (amplitude spectrum), where the frequency value at the maximum amplitude (peak) is monitored. The thickness (or depth to defects) is

related to P-wave velocity and peak frequency of the frequency spectrum by

$$H = \beta C_P / 2f \quad (1)$$

where β is approximately 0.96 for plate-like structures (Sansalone and Streett, 1997). Therefore, when an internal air-filled defect such as delamination lies below the IE test location, the IE resonance frequency is altered indicating the location of the defect from the test surface.

Due to its simple working principle and testing setup, the IE method has been applied various NDT problems in civil engineering field and has shown its special effectiveness in locating and estimating a real size of delamination damages in concrete structures (Schubert and K hler, 2008). However, despite the effectiveness of IE method for NDT of concrete structures, there are still many challenges that prohibit the method from being broadly applied

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in real field applications. One challenge is to ensure good physical contact between the sensor and tested concrete surface; poor physical contact gives rise to unreliable and inconsistent signals. Moreover, the requirement of physical contact limits practical application to large civil infrastructures such as concrete bridge decks and pavements, because contact measurements may require time-consuming surface preparation of rough concrete surface to mount the sensors. All of these issues increase downtime of the structures during the inspection period.

Recently, contactless sensing technique for impact-echo method has been developed using air-coupled sensors (Zhu and Popovics, 2007). An obvious advantage of this contactless sensing technique is that it greatly speeds up the data collection in field, and thus the damage detection can be processed rapidly. The basic idea of air-coupled sensor based IE is that the generated wave motion of the surface generates acoustic waves that “leak” into the surrounding fluid, e.g. the air. Although the magnitudes of these waves are very small due to large acoustic impedance mismatch between solid and air, air-coupled IE can detect these leaky wave components in the air, using an air pressure sensor, to characterize the surface motions indirectly. Therefore, the testing setup and signal processing is the same as the conventional IE except for the sensing unit. Unfortunately, however, widespread application of contactless IE method is hindered by high cost of sensor, external power source, and acoustic shielding that normally are required with conventional high-end air pressure sensors. The set-up cost for testing equipment is one of the principal concerns for field implementation of NDT techniques.

The aim of this study is to explore the feasibility of using low cost, unpowered, unshielded dynamic microphones for contactless sensing of IE signals for delamination damage detection in concrete

structures. IE tests on a delaminated concrete slab were conducted and the results were used to assess the damage detection capability by the low cost system.

2. Air Pressure Sensors for Contactless Sensing

The types of air pressure sensor can largely be categorized into two types: condenser sensors (capacitance change type) and dynamic microphones (electromagnetic induction type) (Borwick, 1990). A main difference between two types is the principle by which they convert acoustic phenomena to electric signals. In condenser sensors as shown Fig. 1(a), one plate (diaphragm) of a capacitor in the condenser sensor is stretched tightly by a supporting ring and placed close to a second plate (backplate). An externally applied electric potential is applied between the plates so that as the stretched plate moves due to air pressure. The motion changes the capacitance of the element, which forces charge to flow from plate to plate as the voltage is held constant. The electric current is made to flow through a very large resistor and the resulting voltage drop is amplified to become the output of the sensor. Some condenser sensors use a permanently charged plate, usually for the backplate, instead of an applied voltage to polarize the capacitor: they are known as “electret” sensors. However, the electret sensor (or sometimes called pre-polarized condenser sensor) still requires an applied voltage to power the electronics (Borwick, 1990). On the other hand, a dynamic microphone is based on the simple principle that a moving conductor within a magnetic field generates a current through electromagnetic induction. Referring to Fig. 1(b) (<http://www.media-college.com/audio/microphones/dynamic.html>), as force is exerted on the diaphragm by air pressure changes, the diaphragm and attached coil moves in and out through the magnetic field, producing a voltage in the coil which is proportional

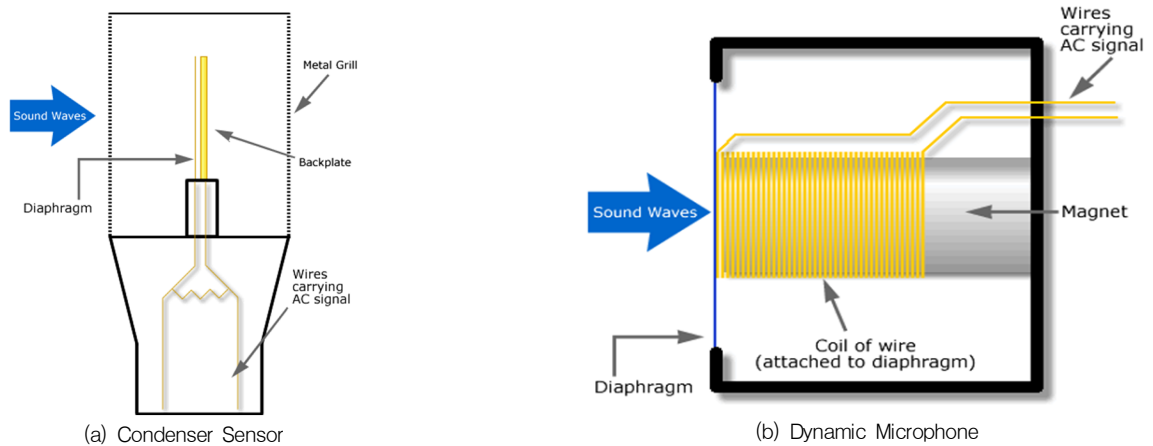


Fig. 1 Schematic Diagram of Dynamic Microphone

to the air pressure.

An advantage of the condenser sensor stems from its low mass moving element, making it easier for small, air pressure changes across a broad range of frequencies to generate a proportional output voltage. Since the mass of a coil of wire in the dynamic microphone is relatively large, it does not move easily enough to allow the small air pressure variations to produce a measurable voltage. Furthermore, dynamic microphones are not effective for sensing frequencies above 20 kHz. On the other hand, condenser sensors require an externally supplied source of electric potential to operate, which is a limitation with regard to field application and increase the costs of the system. In the previous work on non-contact IE sensing (Zhu and Popovics, 2007), they employed a sensitive pre-polarized condenser sensor (Model name: 377C01, a product of PCB Inc.), which costs around 3500 USD itself, and furthermore requires a power source and signal conditioner unit.

3. Experimental Study

3.1 Low Cost Air Pressure Sensor

Many dynamic microphones are commercially available, offering different sensing characteristics. In this study the SM58[®] (a product of SHURE Inc.)

dynamic microphone, which is normally used for music and voice recording, was chosen. The working frequency range of SM58[®] is 50 - 15000 Hz and the sensitivity is 1.85 mV/Pa (Model SM58[®] Dynamic Microphone Specification Sheet). Although the range and the sensitivity of SM58[®] are narrower and lower, respectively, than the condenser sensor used previous studies (4 - 80000 Hz; 4 mV/Pa) (Zhu and Popovics, 2007), they offer notable practical advantages: no external power source is required, they are rugged and durable, and they have relatively low cost. In the United States, the market price of one SM58[®] including necessary accessories such as cables is around 150 USD. Other models of dynamic microphone range in price from 200 to 500 USD. Although the dynamic microphones offer these benefits, the sensitivity and detection capability for concrete NDT have not been established to date.

3.2 Test Specimen and Setup

Since the main purpose of this study is to evaluate the utility of dynamic microphones for air-coupled IE as reported by Zhu and Popovics, the same concrete slab specimen will be used in this study. The slab is nominally 0.25 m thick with 1.5 m by 2.0 m lateral dimensions. The measured nominal P-wave velocity of the concrete was 4100 m/s.

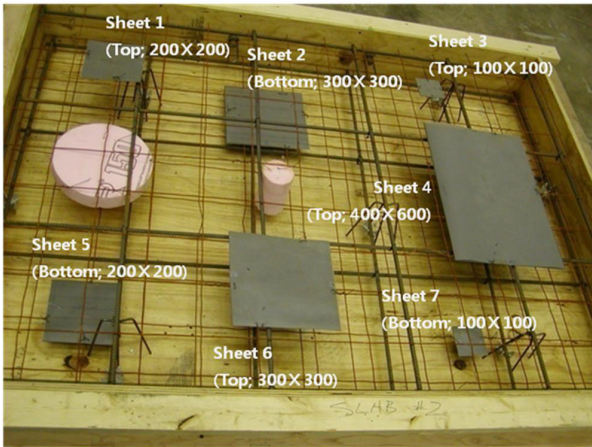


Fig. 2 Locations and Sizes of Simulated Delaminations in Test Specimen

This results in a full-thickness IE frequency of 7.81 kHz assuming $\beta = 0.96$ in Eq. (1). In this slab specimen, artificial delaminations with various sizes and depths were simulated by embedding six double-layer plastic sheets (5 mm thickness). The size and layout of the simulated delaminations are shown in Fig. 2 (Zhu and Popovics, 2007). Note that the sheet numbers are identical to the delamination numbers in the subsequent section. Four delaminations were located 55 mm below the top surface (shallow delaminations), and another three were 195 mm below the top surface (deep delaminations). The testing setup of non-contact IE sensing is shown in Fig. 3. The configuration is similar to conventional IE except there is no contact between the sensor and the test surface. A steel ball (15 mm diameter) is used to generate leaky IE waves from the slab.

4. Results and Discussions

4.1 Leaky IE Signal Measurements

Individual point tests were conducted over the center of each delamination zone. The detected leaky signal using dynamic microphone is then digitized and stored for further signal processing. Each transient signal is collected for 8 ms with a



Fig. 3 Testing Configuration of Contactless Impact-Echo Sensing

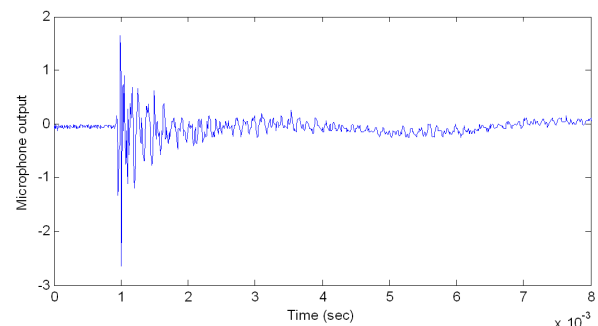


Fig. 4 Example of Measured Leaky IE Signals (at the center point on Delamination # 3)

sampling interval of 10 μs . The distance between microphone and concrete surface is set to 1 cm, and no acoustic shielding around the microphone was used. Fig. 4 shows a typical captured time history, showing that the dynamic microphone can sense the leaky IE response at a reasonably high signal to noise ratio. The distribution of resonant peak frequencies from the measured leaky IE time signals at each test point are seen more easily in the frequency (amplitude) spectrum, which was

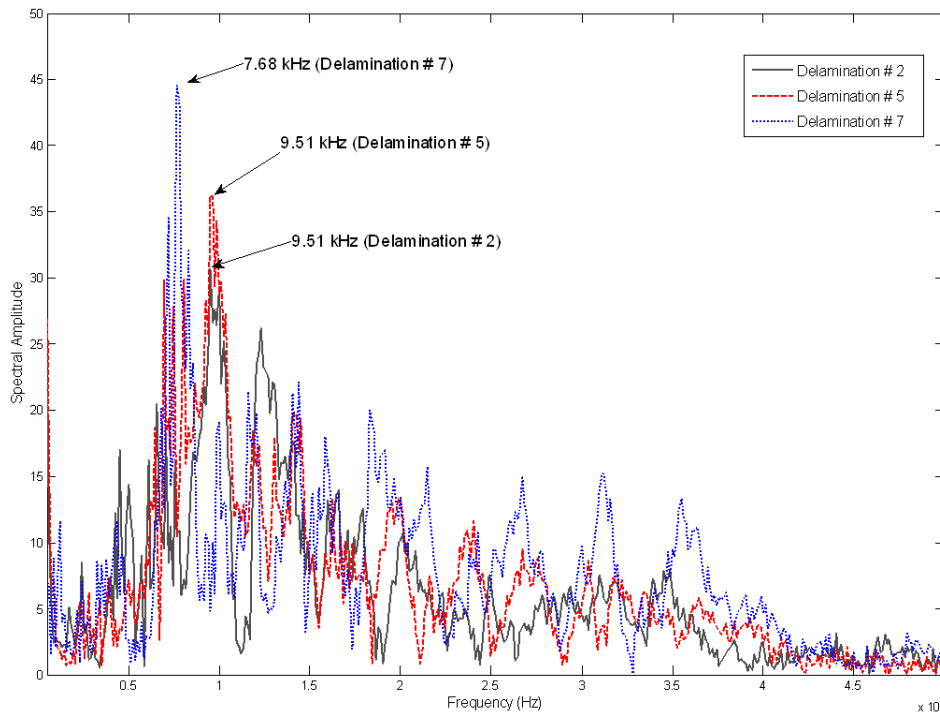


Fig. 5 Fourier Spectra of Measured Leaky IE Signals for Deep Delaminations

obtained by taking FFT of the time signals.

4.2 Detection Capability for Deep Delamination Cases

Fig. 5 shows the amplitude spectra for signals obtained over bottom (deep) delaminations, while Fig. 6(a) and (b) show those over top (shallow) delaminations. The spectra obtained over the deep delaminations tend to have lower spectral amplitude and more spurious peak responses than those obtained over the shallow delaminations. The predicted peak frequency (using Eq. (1) assuming $C_p=4100$ m/s) for the leaky IE signal obtained over deep delamination #2 is 10.1 kHz. The obtained spectrum shown in Fig. 5, however shows several peaks, has one significant peak occurring at 9.51 kHz. It is worth noting that small discrepancies between the measured peak frequency from the predicted value can be possible due to errors in P-wave velocity estimation or signal processing. It is clear that responses with frequencies higher than

those for the defect-free full thickness slab are excited. The spectrum obtained over delamination #5 shows a clear peak frequency near the expected frequency (computed by Eq. (1)) for the defect.

Delamination #5 has the largest areal extent of the deep delaminations. In contrast, the peak frequency for the leaky IE signal obtained over deep delamination #7 which has the smallest areal extent of deep delaminations, is 7.68 kHz and which does not correspond to its depth frequency (10.1 kHz). The measured peak frequency 7.68 kHz is slightly lower than the expected resonant frequency of 7.87 kHz for the defect-free slab and this shifting behavior suggests possible presence of delamination (Model SM58[®] Dynamic Microphone Specification Sheet); similar results have been reported in previous studies (Zhu and Popovics, 2007). However, it is worth noting that since the difference is slight (189 Hz) enough to fall that in the resolution error range of the dynamic microphone, a shift in frequency for the small and deep delamination may not be a reliable indicator

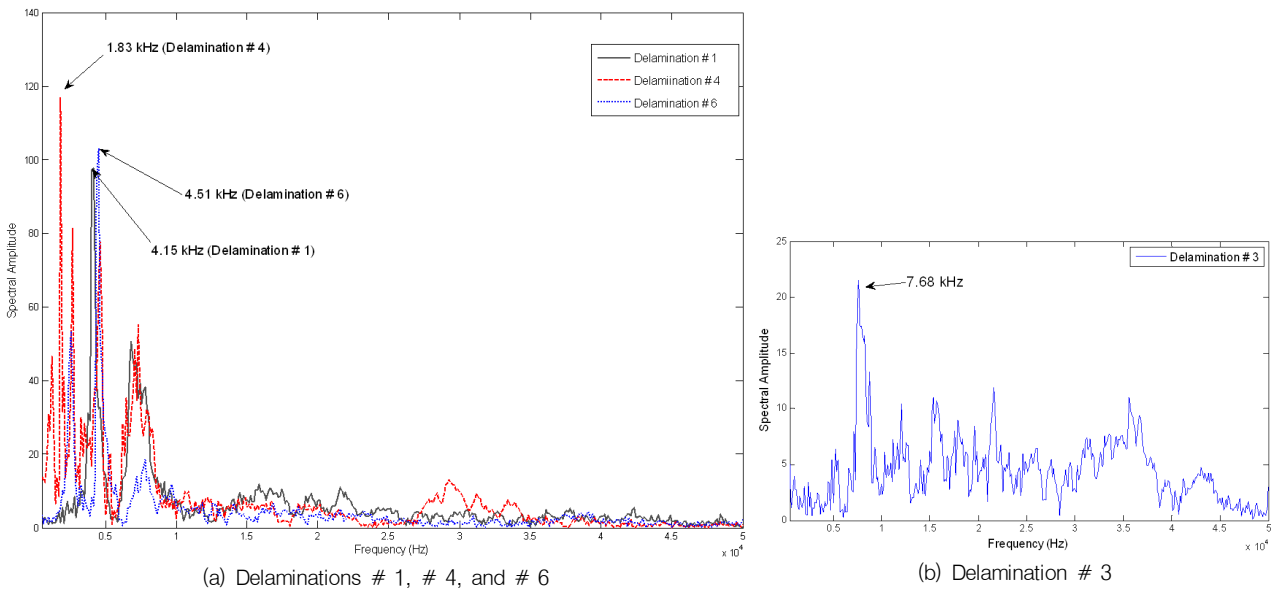


Fig. 6 Fourier Spectra of Measured Leaky IE Signals for Shallow Delaminations

for the delamination detection using the dynamic microphone.

4.3 Detection Capability for Shallow Delamination Cases

For shallow delaminations, the peak frequencies of the leaky IE signals are lower than the full thickness frequency as shown in Fig. 6(a). In those cases, the peak frequencies do not correspond to the IE mode, but are set up by flexural vibration modes. To illustrate the flexural vibration behavior of the large shallow delamination, the natural frequency of fundamental flexural vibration mode of delamination # 1 (length 200 mm, width 200 mm, thickness 55 mm) is calculated using classical vibration theory of simply supported plate (Rao, 2007). Note that perfect agreements between the analytical and experimental results are not expected because of the unknown edge boundary conditions of actual delaminations. The calculated natural frequency is 5.53 kHz assuming typical values of concrete properties ($\rho=2300 \text{ kg/m}^3$, $E=20 \text{ GPa}$, and $\nu=0.2$). This frequency value agrees with the test result for the delamination #1 and confirms

that the peak frequencies formed for shallow delaminations are dominated by flexural vibration. It should be noted that the peak frequencies from shallow delaminations are not necessarily restricted to the fundamental (1st) mode. Depending on the impact and sensor position with respect to the defect location, the higher harmonic modes of plate flexural vibration may be presented in the response signals (Model SM58[®] Dynamic Microphone Specification Sheet). The results indicate that the presence of shallow delaminations can be detected by observing dominant frequency components in the low frequency region, i.e. lower than the full thickness frequency; this is seen in Fig. 6(a). However, not all shallow delaminations exhibit a clear flexural frequency response. As shown in Fig. 6(b), shallow delamination #3, which has small areal size (100 mm by 100 mm) shows neither a low frequency flexural vibration mode nor a high frequency resonance over the delamination, expected at 35.8 kHz using Eq. (1). It cannot be detected signals above 20kHz with dynamic microphones regardless of the frequency content of an impact source; this is one drawback of using dynamic microphones. As a result the observed peak

frequency over delamination #3 is 7.68 kHz, which is the same with the result for deep delamination #7. It is noting that the high sensitivity air pressure sensors used by others can sense vibrations at much higher frequencies, up to 60 kHz.

5. Conclusion

In this study, the feasibility of using low cost, unpowered, unshielded dynamic microphones is experimentally investigated for cost effective non-contact sensing of IE signals in concrete structures. Results showed that a dynamic microphone can capture meaningful impact-echo phenomena from a delaminated concrete slab in a non-contact manner, without external power supply, signal conditioner and special acoustic shielding. Deep delaminations with larger areal size are more likely detected by monitoring peak frequency location. Similarly, shallow delaminations with larger areal size are readily detected by observing strong peak behavior in low frequency. These findings suggest that dynamic microphones are an excellent cost effective alternative to expensive high-end condenser sensors for air-coupled IE sensing in concrete slabs.

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요 지

본 논문에서는 비접촉식 충격-반향 기법을 이용한 콘크리트 구조물의 손상 탐지에 있어서 비용 효율성을 높이기 위한 다이 나믹 마이크로폰의 적용 가능성에 대하여 알아보았다. 박리 손상이 인공적으로 모사된 콘크리트 슬래브 실험체에 대하여 비접촉 충격-반향 실험을 다이 나믹 마이크로폰을 이용하여 수행하였으며 저비용 센서 시스템의 손상 탐지 성능을 분석하였다. 실험 결과 다이 나믹 마이크로폰으로 의미있는 신호의 측정이 가능하며, 또한 콘크리트의 박리 손상도 고성능 음압 센서만큼 명확하게 검출 가능하다는 것을 알 수 있었다.

핵심 용어 : 충격-반향기법, 비접촉 측정, 저비용 음압 센서, 다이 나믹 마이크로폰