Defect Detection of Concrete Structures through Sounding Data Analytics

R. Cao[1], A.K. Agrawal [2]

[1] *Grad. Student, The City College of New York, NY, USA, email: rcao000@citymail.cuny.edu*

[2] *Professor, The City College of New York, NY, USA*

Abstract

Impact sounding has been recognized as an effective technique to detect delamination in concrete structures, such as concrete decks. An enormous amount of sounding data can be generated/collected by the autonomous inspection systems equipped with impactors and microphones. However, the main challenge in the practical application of this technology is the development of advanced data analysis approaches for identifying defects from impact sounding data. In this study, the empirical mode decomposition (EMD) analysis and power-spectral density (PSD) analysis are combined to extract useful features of sounding data generated by the impact hammer. It has been found that the EMD method can effectively eliminate noise from the captured data during the identification of features such as the fundamental frequency. Based on extracted features, a defect contour of the inspected structure can be generated for fast decision making and reliable inspection ratings of concrete structures.

1. Introduction

Impact sounding has been proven to be more effective than the ground penetrating radar (GPR) to detect delamination in concrete structures, and cable ducts and anchorages (Scott et al. 2003, Hurlebaus et al. 2017). The main challenge in the practical application of this technology is the development of advanced analysis approaches for impact sounding data that can be used for identifying defects. For example, methods such as power-spectral density analysis, evolutionary neural network, principal component analysis and time-domain features analysis have been used by researchers in assessing the bonding integrity of the tile–walls (Tong et al. 2006a, Tong et al. 2006b, Tong et al. 2008, Luk et al. 2010 and 2011). Their work has shown the effectiveness of impact sounding approach in detecting bonding integrity of tile walls. In their studies, the effects of noise have been recognized as the main issue that affected the quality of the results. Compared with tile walls, the surface of the concrete bridge deck is considered to be rougher or more irregular, which could cause more noise when impact sounding is used (Popovics 2010). Recently, Sun et al. (2018) proposed a new type of ball chain to reduce the noise from the conventional chain dragging for concrete delamination detection. However, chain dragging devices are mainly used for scanning the top surface of the bridge decks, which have limited applications for inspecting other concrete structures, such as columns, beams, and the bottom surface of the deck. Hammer sounding has been recognized as a more versatile way to detect local delamination in a variety of concrete structures, while the noise issues associated with hammer sounding have not been well resolved (Popovics 2010).

In this research, the empirical mode deposition (EMD) method and power-spectral density (PSD) analysis are used to extract useful signals from hammer sounding data for the defect detection on an engineered concrete slab. It is found that the EMD method can effectively eliminate noise from the captured data during the identification of features, such as the fundamental frequency. The extracted fundamental frequencies from the hammer sounding data are found to be able to detect different defects in concrete structures, such as shallow delamination, honeycomb, and void. Further work should be carried out to study the effect of hammer size on defect detections in concrete structures, especially for deep delaminations.

2. Impact Sounding Test description

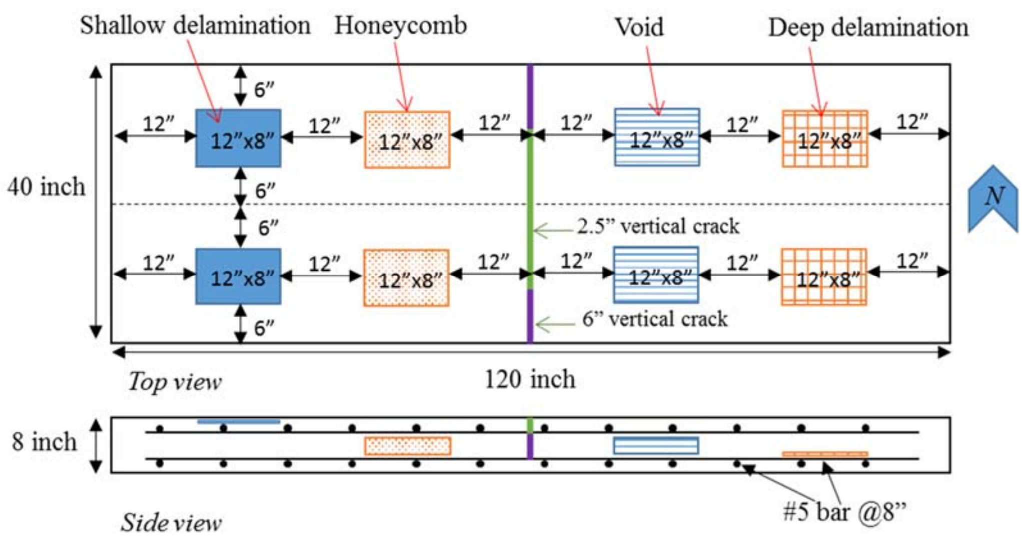

Fig. 1. Design of the concrete slab with engineered defects

In order to collect test data to develop/verify signal processing tools, a concrete slab with known engineered defects at the Turner Fairbanks Highway Research Center of FHWA has been tested. Fig. 1 shows the layout of the slab. The dimension of the slab is 40 inch by 120 inch and it has a thickness of 8 inch. In the slab in Fig. 1, four different artificial defects were designed and embedded in the concrete slab: shallow delamination, honeycomb, void, and deep delamination. The delaminations were simulated by plexiglass sheets, which were placed at depth of 2.5 and 6 inches. The honeycomb was created by loose aggregates and the void defects were built using styrofoam board. Detailed information about the construction of the slab with defects can be found in Lin et al. (2018).

Fig. 2(a) shows the setup of sounding excitation and data acquisition systems. A conventional hammer was used as the sounding source to excite the surface of the concrete slab. For the data acquisition, a common vocal microphone together with a USB-port sound card connected to a laptop enabled the recording of the signal during the test. The microphone was shielded with a foam cup, which helped insulate the ambient noise and direct the sounding waves to the microphone. The general mechanisms of defect detection using hammer sounding are illustrated in Fig. 2(b), where the sounding waves transmitted from the hammer impact were reflected by the defects and collected by the vocal microphone for further data analysis.

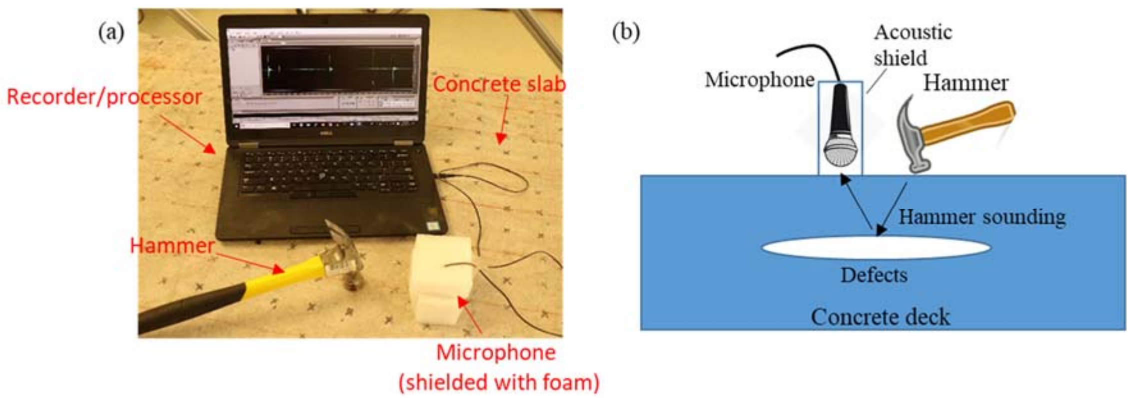

Fig. 2. Test setup: (a) sounding instruments; (b) acoustic sounding mechanism

3. Frequency Spectrum Analysis

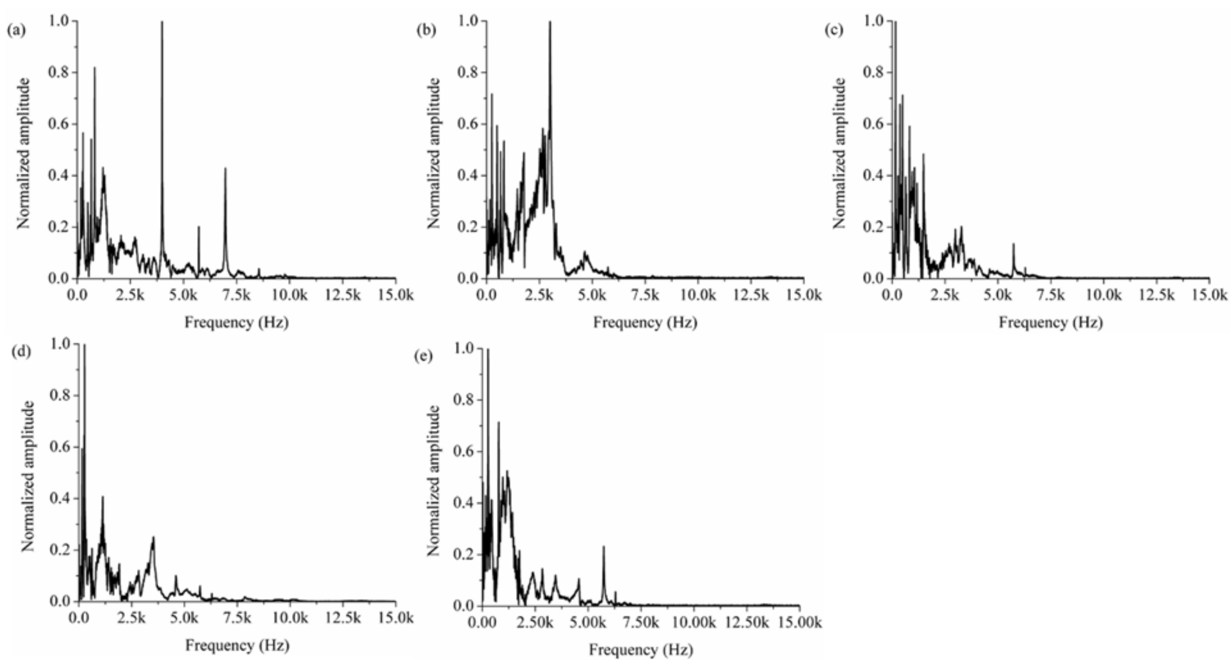

Fig. 3. Fourier spectra of hammer sounding for 5 different defect conditions: (a) no delamination; (b) shallow delamination; (c) honeycomb; (d) void; (e) deep delamination

Fig. 3 compares the typical Fourier spectra of hammer sounding data from 5 different defect conditions. In Fig. 3, the signal for no delamination case of Fig. 3(a) show two sharp spikes in a relative high-frequency range (larger than 4 kHz), while the frequency distributions of signals from the defect zone are relatively flat and mainly located in the low-frequency range, less than 4 kHz. Also, all 5 cases have multiple peaks in the extremely low-frequency range of less than 2.5 kHz, which represents the mixing of noises and flexural mode signals of the slab. Since the sounding features in low frequency are usually correlated with defects, it is important to filter out the unnecessary noise effects and keep the useful signals for further analysis.

4. Empirical Mode Decomposition of Hammer Sounding Data

In this study, the EMD method was used to remove the noise from the sounding signals. EMD is an adaptive data analysis tool that is commonly used to break down any complicated signal set into several components, which usually pertain to different vibration modes and different physical meanings. These components can also be described as intrinsic mode functions (IMF), which build a nearly orthogonal basis for the original data. Fig. 4 shows the Fourier spectra of decomposed hammer sounding signals using the EMD method. In Fig. 4(a), it can be seen that the low-frequency noises with high amplitude were removed from the original signal and the useful impact sounding signal was well represented in IMF1. The filtered noises were also shown in IMF2 and IMF3. Signals from other defect areas are also showing similar filtering effects by EMD in Fig. 4(b) to Fig. 4(e). By comparing the PSD distributions of IMF1 for different signals, the no-delamination data show much smaller amplitudes in the low-frequency range than those for signals from areas with defects. Also, the difference between deep delamination and no-delamination is relatively small compared with other artificial defects. This observation shows that hammer sounding might be less effective in detecting the delamination as the damage develops in a deeper location.

It is observed from Fig. 4 that the fundamental frequencies of hammer sounding data mostly show the flexural mode of vibration, which is different from the thickness mode normally observed in the impact echo (IE) signals. This is because the width-to-depth ratios of the embedded defects are larger than one, which usually leads to the flexural modes (Kee and Gucunski 2016 and Lin et al. 2018). Also, these artificial defects were closely placed near the edge of the slab, which can also cause flexural modes in the no-delamination regions.

After extracting sounding signals (IMF1) using the EMD method, the distribution of PSD (energy) was used as the feature to detect the four artificial defects in the concrete slab. A defect ratio was defined as the energy from a band of 2.5 to 4 kHz (flexural modes) divided by the energy from the whole frequency range of the signal. A contour of the defect ratio from the concrete slab using hammer sounding is shown in Fig. 5, where the defects corresponding to shallow delamination, honeycomb, and void are well detected and are highlighted on a scale of severity of the defects, where 0 represents no damage and 1 represents severe damage. In the plot, actual locations of embedded defects are marked by red rectangles. It is observed that some of the shallow delamination areas show low damage indexes. When the hammer impacted the middle of the shallow delamination area, the concrete surface responded like a “drum”, which significantly amplified the magnitude of the collected sounding data and the “drum sounding” was found to exceed the threshold value of the microphone. This “drum effect” disrupted the original signal and affected the detection results. The boundary of the defects was still well detected. Further studies on controlling the “drum effect” will be carried out by the authors in the next phase of the project. In this study, the hammerhead had a diameter of 20 mm. Hammers with smaller head could induce sounding signals with higher frequencies. The effect of different properties of hammers on the detection of concrete defects, especially deep delamination, will also be investigated by the authors in future studies.

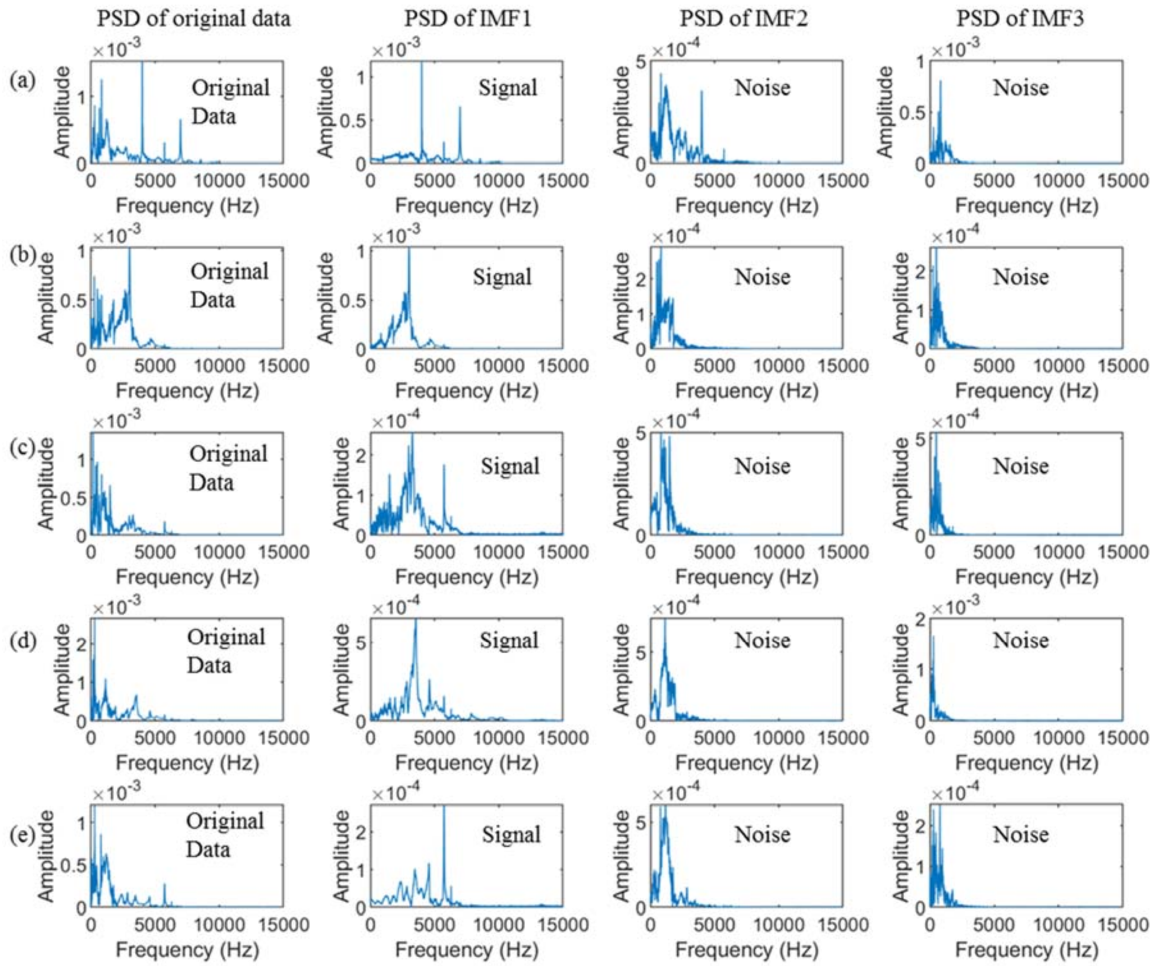

Fig. 4. Empirical mode decomposition on hammer sounding data: (a) no delamination; (b) shallow delamination; (c) honeycomb; (d) void; (e) deep delamination

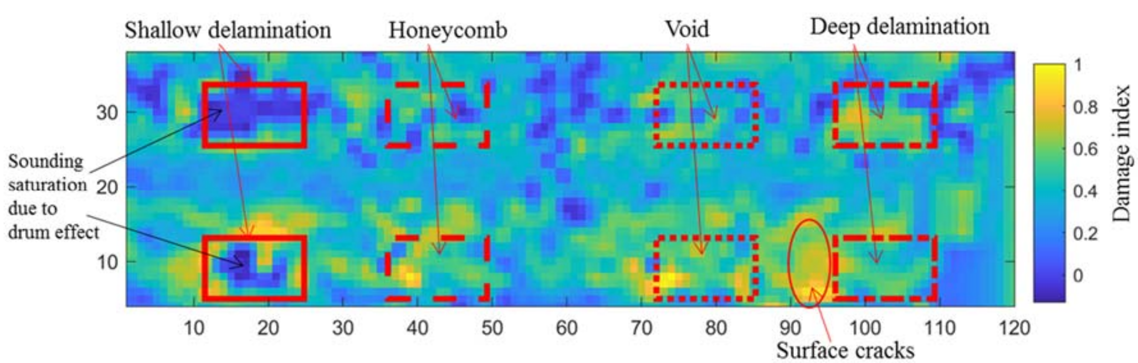

Fig. 5. Damage contour of the slab based on the dominant frequency of hammer sounding data

5. Conclusion

In this study, empirical mode decomposition (EMD) method is used to filter out the noise from the hammer sounding signal. The first intrinsic mode function (IMF) has been found to be the useful sounding signals and other IMFs are the noises, such as the friction between the hammer and the deck surface. The embedded defects in an engineered slab have been well detected based on the features of PSD distribution of the hammer sounding. Most of the sounding signals have been found to be the flexural modes of the slab or defects. Further work should be carried out to study the thickness mode of the slab, similar to impact-echo, by using different sounding sources, such as hammers with different sizes and electronic sounding.

6. Acknowledgments

This project was partially funded by the INSPIRE University Transportation Center (UTC). Financial support for INSPIRE UTC projects is provided by the U.S. Department of Transportation, Office of the Assistant Secretary for Research and Technology (USDOT/OST-R) under Grant No. 69A3551747126 through INSPIRE University Transportation Center (http://inspire-utc.mst.edu) at Missouri University of Science and Technology. The views, opinions, findings, and conclusions reflected in this publication are solely those of the authors and do not represent the official policy or position of the USDOT/OST-R, or any State or other entity. The authors also sincerely acknowledge the support of Mr. Frank Jalinoos and Ms. Hoda Azari of FHWA in accessing the concrete decks for impact sounding experiment.

7. Reference

Hurlebaus, S., Hueste, M. B. D., Karthik, M. M., and Terzioglu, T. (2017). Inspection Guidelines for Bridge Post-tensioning and Stay Cable Systems Using NDE Methods, NCHRP Research Report 848.

Kee, S.-H., and Gucunski, N. (2016). "Interpretation of flexural vibration modes from impact-echo testing." *J. Infrastruct Syst.*, 22(3), 04016009.

Lin, S., Meng, D., Choi, H., Shams, S., and Azari, H. (2018). "Laboratory assessment of nine methods for nondestructive evaluation of concrete bridge decks with overlays." *Constr Build Mater*, 188, 966-982.

Luk, B. L., Liu, K., Tong, F., and Man, K. (2010). "Impact-acoustics inspection of tile-wall bonding integrity via wavelet transform and hidden Markov models." *J. Sound Vib.*, 329(10), 1954-1967.

Luk, B. L., Liu, K., and Tong, F. (2011). "Rapid evaluation of tile-wall bonding integrity using multiple-head impact acoustic method." *NDT & E Int.*, 44(3), 297-304.

Popovics, J. S. (2010). "Investigation of a Full-Lane Acoustic Scanning Method for Bridge Deck Nondestructive Evaluation." Transportation Research Board, Final Report for Highway IDEA Project 134.

Scott, M., Rezaizadeh, A., Delahaza, A., Santos, C., Moore, M., Graybeal, B., and Washer, G. (2003). "A comparison of nondestructive evaluation methods for bridge deck assessment." *NDT & E Int.*, 36(4), 245-255.

Sun, H., Zhu, J., and Ham, S. (2018). "Automated Acoustic Scanning System for Delamination Detection in Concrete Bridge Decks." *J. Bridge Eng.*, 23(6), 04018027.

Tong, F., Tso, S., and Hung, M. (2006a). "Impact-acoustics-based health monitoring of tile-wall bonding integrity using principal component analysis." *J. Sound Vib.*, 294(1-2), 329-340.

Tong, F., Tso, S., and Xu, X. (2006b). "Tile-wall bonding integrity inspection based on time-domain features of impact acoustics." *Sensor Actuat A-Phys,* 132(2), 557-566.

Tong, F., Xu, X., Luk, B., and Liu, K. (2008). "Evaluation of tile–wall bonding integrity based on impact acoustics and support vector machine." *Sensor Actuat A-Phys,* 144(1), 97-104.