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An automatic impact-based delamination detection system for concrete bridge decks

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ABSTRACT

Delamination of concrete bridge decks is a commonly observed distress in corrosive environments. In traditional acoustic inspection methods, delamination is assessed by the "hollowness" of the sound created by impacting the bridge deck with a hammer or bar or by dragging a chain. The signals from such sounding methods are often contaminated by ambient traffic noise and delamination detection is highly subjective. In the proposed method, a modified version of independent component analysis (ICA) is used to filter the traffic noise. To eliminate subjectivity, mel-frequency cepstral coefficients (MFCC) are used as features for delamination detection and the delamination is detected by a radial basis function (RBF) neural network. Results from both laboratory and field data suggest that the proposed method is noise robust and has satisfactory performance. The method can also detect the debonding of repair patches and concrete delamination below the repair patches. The algorithms were incorporated into an automatic impact-based delamination detection (AIDD) system for field application.

1. Introduction

In, 2009, the American Society of Civil Engineers (ASCE) estimated that more than 26% of bridges in the US were either structurally deficient or functionally obsolete and an annual investment of $17 billion is needed to improve the current bridge conditions [1]. The priority has shifted from building new structures to inspection, assessment and maintenance of existing structures [2]. Reinforced concrete bridge decks continuously degrade due to normal traffic and environmental exposure. Delamination is the major form of deck distress. This type of damage usually initiates underneath the surface due to corrosion of the steel reinforcement and subsequent freezing and thawing of the water in the cracks, and cannot be detected by visual inspection in its early stages. With time, the delamination propagates and leads to spalling of the upper surface of the bridge deck. Small delaminated areas can be repaired by patching the affected area. A very large area of delamination will usually result in the replacement of the entire deck, which is expensive and causes significant user delay. It is therefore necessary to detect delamination at an early stage to reduce the cost of repair.

Many methods have been considered for the inspection of bridge deck systems including ultrasonic pulse velocity [3,4], impact-echo [5–7], ground penetrating radar [8,9], infrared thermography [10,11] and sounding methods [6,12,13]. The ultrasonic pulse velocity method measures the speed of the ultrasonic wave in the concrete using the travel time of the pulse and infers the presence of damage by a reduction in the measured pulse velocity. The impact-echo method locates the damage by identifying changes in the peak frequencies in the frequency spectrum. Both methods require that the sensors be fully coupled to the deck for reliable measurements. This process is time consuming and impractical for rapid field inspection of a large area of a bridge deck. In addition, the signal obtained from the impact-echo test in real situations can be difficult to interpret. When the surface of the defect is irregular, multiple peaks may appear in the frequency spectrum and it is difficult to identify the peak associated with the defect. Ground penetrating radar is a non-contact, non-destructive and fast method, but it is not sensitive in detecting delaminations, voids and cracks filled with air because the contrast between the dielectric constants of air and concrete is small. Infrared thermography can effectively detect shallow delaminations, but it can only be performed when the temperature is changing, which makes the method environment dependent.

Traditional sounding methods for delamination detection involve: bar or hammer tapping of the deck, or dragging a chain over the deck, and listening to the change in the sound.

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The delamination is the separation of a layer of concrete from the main body of the deck and can be viewed as a plate with its ends fixed to a rigid body of concrete. If the impact energy is enough to excite the flexure mode of the ''plate,'' the delaminated part of the deck vibrates at a frequency that produces a hollow sound. Concrete with no delamination produces a clear, ringing (high frequency) sound. Standard test procedures are defined in ASTM D4580-2003 [14]. Mechanical sounding has the advantage of being fast, simple and inexpensive when compared with other sophisticated techniques and is the most prevalent method used for the inspection of concrete bridges following visual inspection [15]. However traditional sounding methods have several problems. First, delamination detection is subjective and operator dependent. Second, the effectiveness of sounding is affected by the level of ambient noise. Although, several attempts have been made to improve sounding methods, research on this topic is still quite limited. In the 1970s, researchers at the Michigan Department of Transportation (MDOT) designed a cart-like device for delamination detection [13]. The impulse was created by the chattering of two metal wheels with the concrete deck and the resulting vibration of the concrete was captured by a transducer coupled to the concrete through soft tires and liquid in the wheels. The recorded signals were first truncated to retain the signal 5 ms after tapping and filtered by a fixed band pass filter with cut-off frequencies at 300 and 1200 Hz. The processed signals were recorded on charts. The audible signal was played through headphones and the presence of delamination in the concrete was detected by listening to the signal. This method was automatic, but the signal processing algorithm was primitive. The Iowa Department of Transportation investigated a device called DELAMTECT and found it effective in detecting delaminations in bridge decks, but it required careful calibration and extensive training of the inspector [16]. In the 1990 s, researchers at Mississippi State University analyzed sound signals created by a chain-drag [12]. The traffic noise was isolated by sound proofing around the chains. A computer algorithm used linear prediction coefficients (LPC) to analyze the recorded signals and perform the delamination detection. Although this technique showed promise, the method had two major drawbacks. First, the traffic noise was reduced only by physical isolation, which can be ineffective at high noise levels and for complex sound fields encountered on highway bridges. Second, traffic noise is usually non-stationary and simple filtering using LPC can be inadequate.

This paper describes an effective method for delamination detection that can eliminate ambient noise and does not require the subjective judgment of a well-trained operator. The following are implemented in the proposed method:

1. To reduce the influence of traffic noise, a noise canceling algorithm is used to separate the ambient noise from sound measurements obtained by impacting concrete bridge decks with a stainless steel rod.
2. To eliminate subjectivity in the delamination detection, specific features are used to parameterize the filtered signals and facilitate detection.
3. An automatic delamination detection algorithm is used to identify delaminations using the parameters of the signals generated by the impact.

These steps are briefly described in the following sections:

2. Description of algorithms

Noise cancellation is a basic yet difficult problem. Fig. 1 shows the power spectra of typical impact and traffic noise signals. There is considerable overlap in the spectra indicating that the noise cannot be eliminated using simple band-pass filters. Fig. 2 shows that the properties of the traffic change in time due to changing traffic patterns. Due to the non-stationarity and the unpredictability of the traffic noise, the noise canceling algorithm must be adaptive and require no prior information about the noise. In this research, traffic noise was canceled by an algorithm based on independent component analysis (ICA) [17], called modified ICA. Because the signal generated by the impact and the traffic noise are statically independent, they can be separated by minimizing the statistical dependence between their recorded outputs. The modified ICA algorithm consists of the following steps:

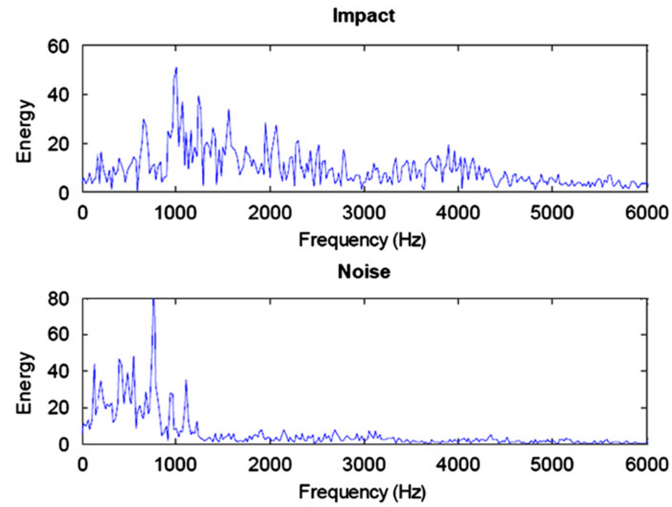

Fig. 1. Spectrum of impact-generated sound and traffic noise.

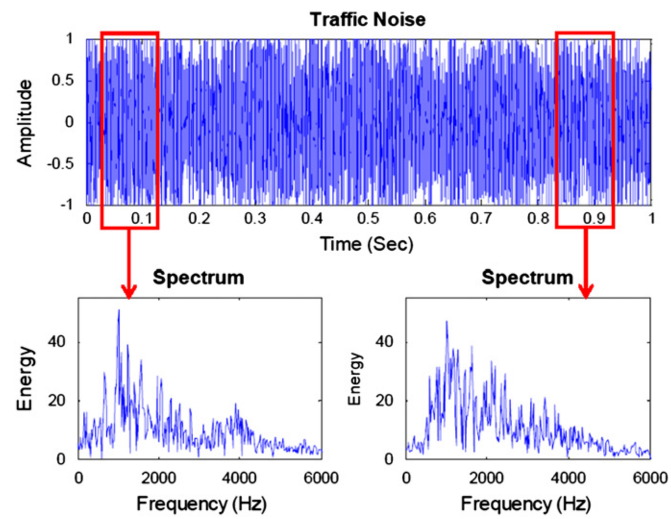

Fig. 2. Non-stationarity of the traffic noise.

Step 1: A ''convolutive sphering'' [18] on the recordings is performed. In this step, delayed versions of the recording are used as additional recordings. The number of delayed versions are determined by the distance between the two recording devices (microphones).

Step 2: Traditional ICA is applied to the rearranged input. The outputs of this step are delayed and scaled source signals [19].

Step 3: The similarity or the ''separations'' between the independent components (outputs of ICA) from Step 2 are calculated based on a correlation-based criteria [18].