ISSN 1997-1400 Int. J. Pavement Res. Technol. 6(6):730-736

Health Monitoring of Concrete Bridges and Vehicle Loads Correlation Analysis Based on Acoustic Emission

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Abstract: In recent years, with the development of digital acoustic emission (AE) systems and the improvement of signal processing technique, acoustic emission technology has been more and more widely used in the research of dynamic processes of compression, tension, impact, fatigue, crack, and fracture of materials and structures. Since correlation analysis of vehicle loads during the monitoring period is lacking in previous concrete bridge structure health monitoring with AE, it is hard to identify the form of AE signals when vehicles cross the bridge. This paper is the first study to combine acoustic emission technique with dynamic monitoring of vehicle loads in bridge structure health monitoring. It studies the feasibility of applying AE technique to existing concrete bridges and discusses characteristic forms of acoustic emission when vehicles pass the bridge. The monitored bridge is a typical highway concrete bridge with small box girders. AE sensors were located on the web, deck plate, and bottom plate of the box girders; a weigh-in-motion system (WIM system) was located in the pavement of bridgehead. The clocks of the two systems were synchronized in order to coordinate the relationship between AE and the weight and velocity of vehicles when they pass the bridge. Based on the analysis of recorded data in 24 hours, the forms of AE signals and the influencing factors were studied; the response characteristics of AE in different locations of the box girder were detected. Then, the correlation between vehicles' dynamic loads and AE features was studied. Reference datum of healthy concrete bridges under the vehicle loads was established, which laid the foundation for further monitoring and evaluation of concrete bridges by AE.

DOI: 10.6135/ijprt.org.tw/2013.6(6).730
Key words*: Acoustic emission; Concrete bridge; Crack; Damage; Health monitoring; Vehicle load.*

Introduction

Acoustic emission (AE) is a technique to measure elastic waves generated by sudden changes, which occur locally in materials due to deformation, cracking, transformation, and so forth [1]. When the structure is under load conditions, materials like concrete or steel will emit energy in form of elastic waves. In concrete, micro cracking and crack growth are the principal sources of these emissions [2]. While AE is sensitive to the changes of materials, it is widely used in non-destructive inspection of bridge structures, aerospace, ships, chemical containers, and so on.

Researchers began to apply the AE technique to bridge structure monitoring in the 1970s, while Pollock and Smith first used the AE technique to monitor a portable military bridge, with results of successfully identifying amplitude distribution and crack location [3]. After that, AE was introduced to monitor steel bridges, which confirmed the powerful capability of using AE to find and to locate fatigue and fracture cracks. In recent years, some researchers like Fricker applied AE to evaluate concrete bridges [4], demonstrating that AE can correctly identify concrete damage and assess the damage degree. Colombo has conducted a series of experiments based on AE technique and developed the quantitative analysis method by b-value [5]. Nair and Cai have applied AE technique to both concrete bridges and steel bridges. They used parameter statistical analysis and quantitative analysis of recorded data to evaluate the existing bridges [6]. In China, Li and Ou used an AE parameter relationship map to identify whether a wire is in good condition [7]. Recently, Wang conducted the fatigue cracking monitoring and evaluation using AE sensors supported by Physical Acoustic Corporation for existing steel bridges in China [8].

To apply AE to concrete bridges in China, the authors have conducted a series of site monitoring projects and related research. This paper focuses mainly on AE application to concrete bridges and the correlation analysis of vehicle loads and AE signals. AE signals produced by different live loads are acquired. The correlation between live loads and AE signals was analyzed. Then, the pattern of AE present during a truck or a car passing the concrete bridge was studied. The main factors impacting the number of AE hits and AE energy during vehicles passing were investigated, which lays the foundation for continuous monitoring based on AE technique. Finally, the signal characteristics of AE present at different locations of box girders were summarized, and the bridge working performance was evaluated.

Principle of WIM System and AE System

HI-TRAC 100 is an advanced weighing system which includes two piezoelectric sensors, one induction coil sensor, and a data acquisition unit (shown in Fig. 1). A temperature sensor is set in pavement, which can acquire real temperature information to

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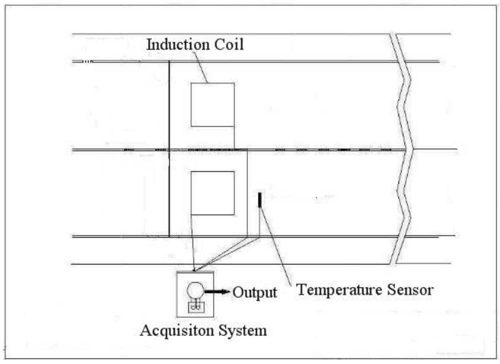
Note: Submitted September 6, 2012; Revised February 28, 2013; Accepted March 14, 2013.



(a) System Layout.

(b) Acquisition System.

Fig. 1. WIM System.

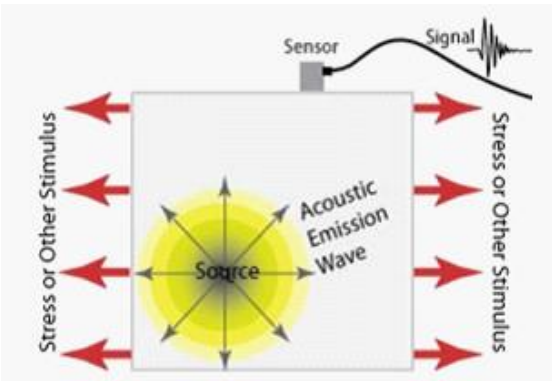


Fig. 2. The Model of AE Signal Production and Spreading.

Fig. 3. Yaoxian Bridge.

provide proper temperature compensation for the system. The controlling unit set beside the bridge is linked to the piezoelectric sensors and the induction coil. When vehicles pass the bridge, the induction coil picks up different responses, and the piezoelectric sensors send the information to the acquisition unit. Then the controlling unit can calculate the specific information of the passed vehicle and record the information. The system can record comprehensive information about the vehicles moving through, such as weight, speed, direction, axle number, and so on.

Fig. 2 shows the model of AE signal production and spreading. When structure or material is in the condition of tension, compression, or impact, the internal crack tip of structure will lead to a transient release of stress that can produce stress waves [8]. When the crack propagates, the stress waves spread in all directions. Then these stress waves could be picked up by AE sensors attached on the surface of structure.

The AE system used in the study is a 16-channel MicroII made by Physical Acoustics Corporation. It can do AE waveform capture and feature extraction simultaneously. The test used 30 kHz (model R3I) and 150 kHz (model R15a) AE sensors.

Basic Information about Site Testing

The subject bridge (Yaoxian Bridge) is a typical highway concrete bridge with four small box girders in Shaanxi province of China, shown in Fig. 3. It is a key bridge of provincial road 305 from Tongchuan to Jiaopin, built in 2006. It is an 8-span pre-stressed continuous box girder bridge with span length of 30 m. Since the bridge is near a coal mine, most of the vehicles are coal trucks. As a result, the bridge is under great load level. The vehicle load of the bridge is diverse, ranging from full-load truck to small car, which results in different signal levels under different vehicle loads. So AE technique should be an ideal choice for monitoring the concrete bridge and providing information about its structural condition.

The TDC 100 WIM system was introduced for site monitoring. The TDC WIM system was located at one end of the bridge, and the time clocks of WIM system and AE system were set at the same. So it is feasible to combine the vehicle load and AE signal to perform a correlation analysis. In combination with stress monitoring, the testing can give a comprehensive correlation analysis and evaluation of the bridge.

The AE equipment used in the bridge monitoring was made by Physical Acoustic Corporation, which includes an independent AE system: Micro-II, R3I, and R15a sensors. The system was controlled by remote Ethernet line, which is suitable for site monitoring. The AE monitoring began on August 23, 2011, and the total monitoring time was more than 5 weeks. The data acquisition frequency is 1MHz, and the length of each acquired burst AE waveform is 1k (1024 data samples). Based on the level of noise in the monitoring site, the threshold level was set at 50 dB.

The No.2 and No.3 box girders of the first span were chosen to be the monitoring region. In order to identify the different signal characteristics of different locations, sensor locations are on the every part of the box girder, as shown in Fig. 4. Sensors No. 7 and No. 11 are on the deck plates; Nos. 2, 5, 9, and 13 sensors are on the bottom plates; the other 10 sensors are on the webs.

In this site testing, two kinds of sensors (R3I and R15a) were adopted to decide which is more effective for concrete structures. One kind is R3I with the 30 kHz-resonant-frequency, used at the same positions of No. 8, 9, 10 sensors; R15a with

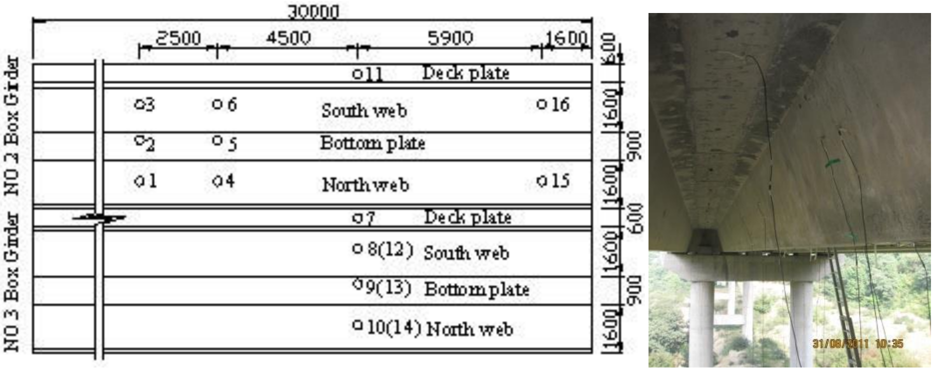


Fig. 4. Sensor Locations (mm).

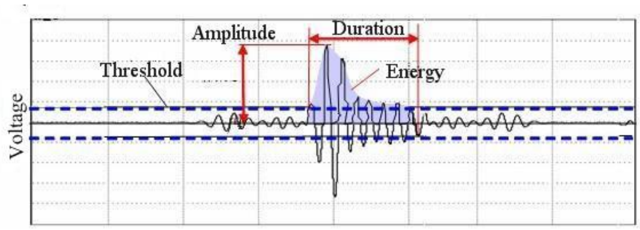


Fig. 5. A Typical AE Signal.

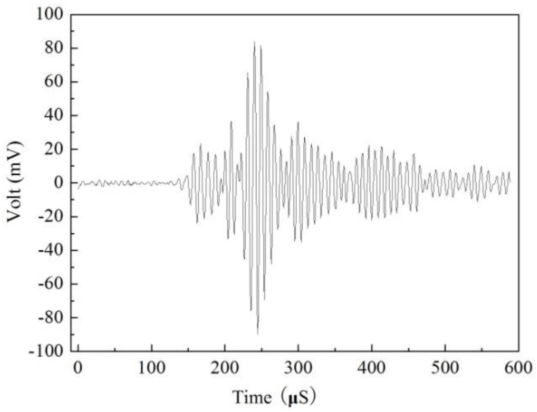


Fig. 6. Typical Signal Induced by Vehicle Load.

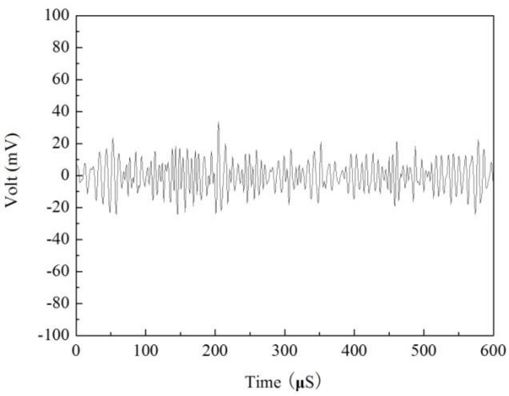


Fig. 7. Signal Induced by Noise.

150kHz-resonant-frequency was located at the same positions of Nos. 12, 13, 14 sensors.

Correlation Analysis

Typical AE Signals

The AE signal is a response of stress wave, which contains information regarding the AE event and the induced source. Typical parameters of an AE signal include amplitude, duration, energy, threshold, and counts, as illustrated in Fig. 5. A typical AE signal is also an indicator of the deformation experienced by bridge element subject to dynamic loading caused by moving vehicles.

In site testing, the condition is very complicated. During the period of crack propagation, the bridge will produce a lot of signals. Most signals are induced by live load, while some scattered signals are not from the live loads, but from on-site environmental noise. Signals induced by vehicles (shown in Fig. 6) show burst fashion; with the sudden rise and rapid attenuation, the peak of the burst signal is easily identified. Signals induced by wind, noise, or insect hit (shown in Fig. 7), whose energy is relatively low are generally chaotic and random. When cars or trucks come across the bridge, many AE hits are generated and the AE amplitude increases sharply [2, 3]. So it is easy for an AE system to filter out signals induced by the noise and recognize signals induced by cars or trucks.

Table 1 shows the total number of AE hits of every channel in 24 hours. From this table, it is obvious that Channel 7 recorded the most signals, and Channels 12 and 14 recorded the lowest amount of signals. No.7 sensor is on the deck, while Nos.12 and 14 are on the webs. In order to decide the relationship between live load and AE signal, the No.7 sensor was studied. Some typical signals are chosen to give a correlation analysis between vehicle loads and signal characteristics.

Since there is a coal mine nearby, many coal trucks cross the bridge every day. Fig. 8 shows an example of recorded information about a typical truck by WIM system; it indicates the vehicle kind is "C:3" (5 axles), the speed is 29 mph, the weight is 46,250 kg and the truck is on Lane 1, and the time is 18:07:42 PM. The relative AE signal is shown in Fig. 9, with the peak voltage surpassing 100mV. When the truck comes cross the bridge, it normally generates more than one burst AE hit with duration in 2 or 3 ms.

Fig.10 shows the information about the common car crossing the bridge, which indicates the vehicle kind is "F:0" (common car), the speed is 46mph, the weight is 1370 kg, the truck is on Lane 2, and the time is 08:06:04 AM. The related AE signal in Fig. 11 shows that the signal has an obvious peak, and the voltage is a little more than 50 mV. Compared to the signal induced by heavy trucks,

Fig. 8. Detail Information of a Heavy Tuck.

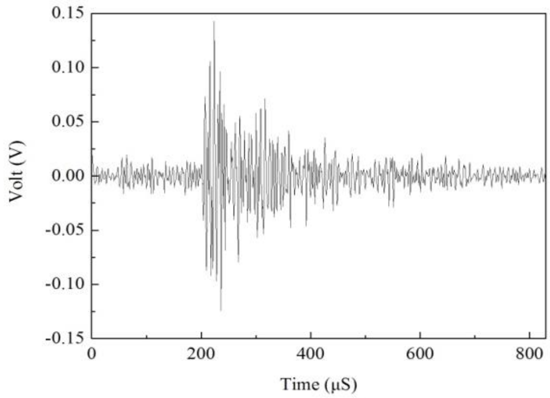


Fig. 9. AE Signal Induced by Heavy Truck.

Table 1. Total Hits of Every Channel in 24 Hours (29 August, 2011).

Channel	1	2	3	4	5	6
AE Hits	23560	19420	30801	18615	2506	32209
Channel	7	8	9	10	11	12
AE Hits	50642	516	23	539	49187	18
Channel	13	14	15	16		
AE Hits	26	12	2871	25030		

Fig. 10. Detail Information of a Car.

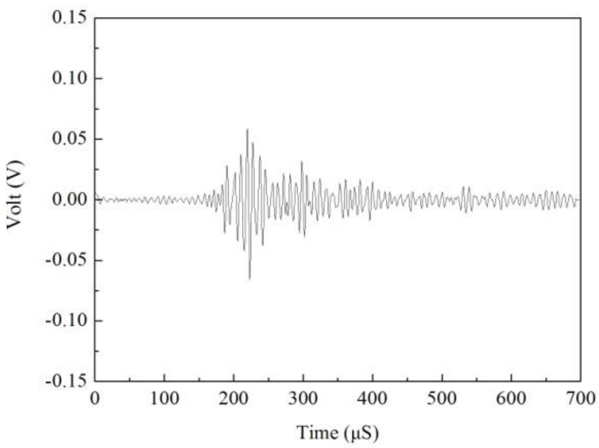


Fig. 11. AE Signal Induced by the Car.

the voltage of the signal induced by the common car is much lower, and the duration of the signal is a little shorter.

Correlation Analysis during 24 Hours.

Table 2 shows traffic volume over 24 hours (August 29, 2011). The total number of vehicles that pass through is 1778, while there are 994 and 784 vehicles that cross Lane 1 and Lane 2, respectively. The largest number of vehicles were Type A (2 axles) vehicles, i.e. 1,053. Types B, C, D, E stand for trucks of 3, 4, 5, 6 axles, respectively; Type F stands for the common bus. Most of the local trucks are 4 axles, so the number of type C vehicles is 507. The specific information of the vehicles is recorded in the weighing system.

Combining Fig. 10 with Fig. 12 indicates simple correlation between vehicle load and the amplitude distribution. The relationship can be summarized as follows: a truck with heavy load will induce large amplitude, while a car of light load will induce small amplitude. From the above figures, the threshold is set at 50 dB; most amplitude is below 70 dB. In the night, there were few vehicles passing, so the beginning of the graph (00:00-06:00) shows few signals; however, from 06:00 to 12:00 there seemed to be more signals, and the amplitude tend to be large. From the vehicle weighing system information, there are more vehicles in daylight, many of which are heavy trucks. The vehicle information and the amplitude graph show a good correlation.

Since the clocks of the WIM system and AE system are

Table 2. Traffic Volume in 24 Hours (29 August, 2011).

Vehicle Kind	A	B	C	D	E	F	Total
Number(Lane 1)	560	24	307	12	29	62	994
Number(Lane 2)	493	19	200	16	19	37	784
Total	1053	43	507	28	48	99	1778

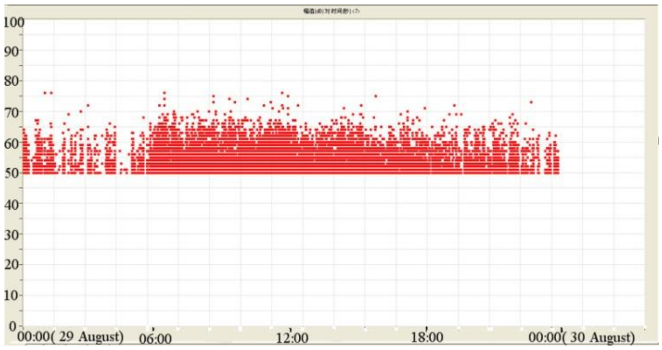


Fig. 12. Amplitude Distribution of AE Signals in 24 Hours (29 August, 2011).

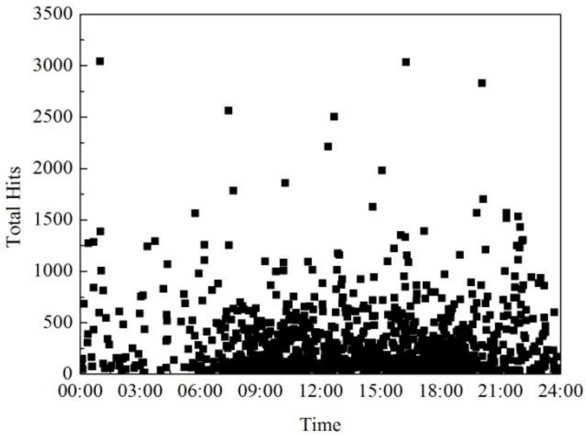


Fig. 13. Correlation of Total Hits and Time.

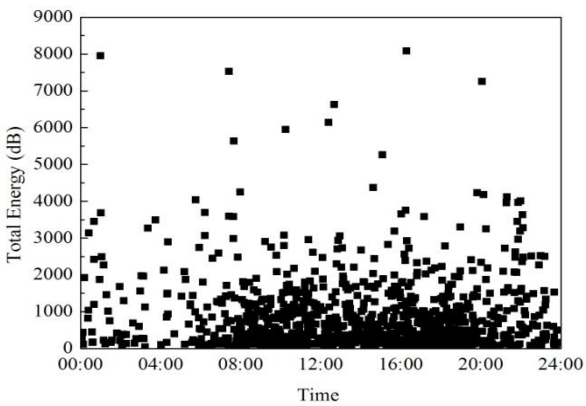


Fig. 14. Correlation of Total Energy and Time.

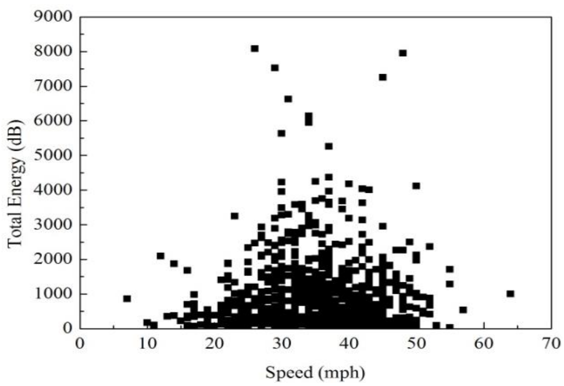


Fig. 15. Correlation of Total Energy and Speed.

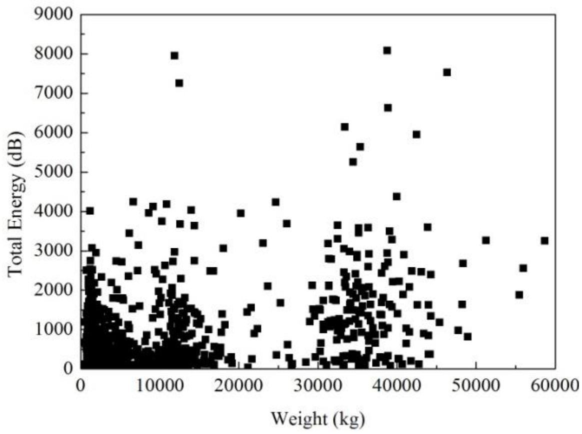


Fig. 16. Correlation of Total Energy and Weight.

synchronized, it is easy to sort out the correlative signals of different vehicles. Fig. 13 shows a 24-hour historical recording of the number of AE hits generated by each vehicle passing. Each dot in the figure represents the number of hit of one vehicle passing. There are more vehicles passing the bridge during the day, shown by the dense distribution of the dots. The majority of vehicles generate the number of hits fewer than 500. The maximum number of hits per vehicle passing is about 3,000, it may be induced by an overloaded truck or by a chain of vehicles crossing the bridge at the same time.

Fig. 14 is a 24-hour historical recording of total AE energy induced by each vehicle passing, and it shows a similar trend with Fig. 13. Most of the total energy induced by a single vehicle is less than 2,000, and the peak energy is around 8,000. Some outstanding points may be induced by special vehicles like tracked vehicles. Signals acquired during the day are much more than that acquired during the night.

Total energy is influenced by speed and weight as shown in Figs. 15 and 16. A speed of 30 to 40 mph is more likely to produce high AE energy because the momentum of the vehicles is high in this range. The vehicles running faster tend to be smaller cars and the vehicles with heavy loads tend to run slowly; both have smaller momentums. Almost all vehicles passed the bridge with a speed of less than 60 mph. All vehicle loads are lighter than 60 tons, and among all passing vehicles, there are many cars weighing less than 5 tons, and there are many trucks weighing about 30 tons to 40 tons. Fig. 16 indicates that heavy weight intends to induce more AE events and generates more AE energy.

Fig. 17 gives the correlation of total energy and momentum, which is the combination of Figs. 15 and 16. It shows a simple relationship between total energy and momentum, i.e. larger momentum induces higher AE energy. From Figs. 15 to 17, it can be concluded that passenger cars have small loads and faster speeds, and very heavily loaded trucks often have low speeds. Both cases may not generate the maximum AE energy. The most important impact factor to the AE events is the dynamic impact generated by a heavily loaded truck with higher speed or by a truck with higher momentum.

Signal Characteristics from Different Positions of Box Girder

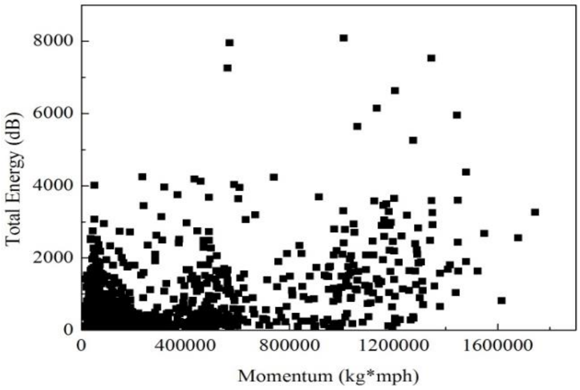


Fig. 17. Correlation of total energy and momentum.

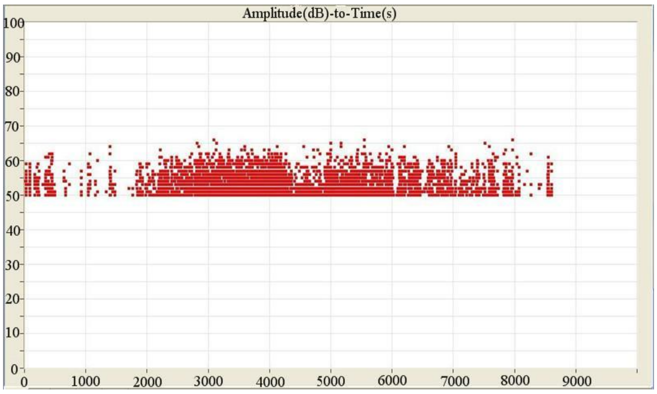


Fig. 18. Amplitude Distribution of Bottom Plate.

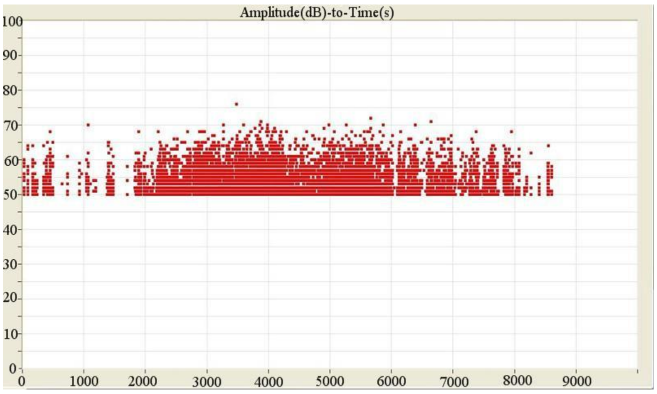


Fig. 19. Amplitude Distribution of Web.

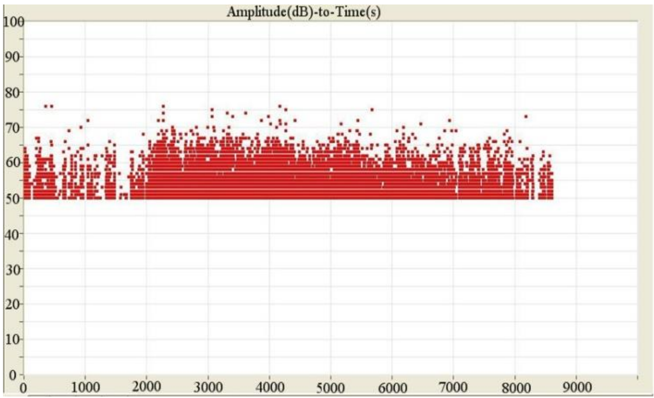


Fig. 20. Amplitude Distribution of Deck Plate.

The No. 2, 6, and 7 sensors are three typical sensor locations of bottom plate, web, and deck plate, which received the most hits among all sensors on the same kind of locations. Figs. 18 to 20 are the amplitude distribution of three different positions. The sensor at the bottom plate recorded fewer hits than the sensors located at web and deck plate of box girder. The AE amplitude at the bottom plate is lower than 65dB. The AE amplitude detected by the web sensor is less than 70 dB, and the amplitude at deck plate is less than 75 dB. Deck plate sensor No. 7 received most AE hits, and the average amplitude level is obviously higher than that of web or bottom plate. Sensors of R3I (No. 8, 9, and 10 sensor) are sure to record more AE hits, while sensors of R15a (No. 12, 13, 14 sensor) record few AE hits.

All the observed signal amplitudes are at a relatively low level, and there is no amplitude exceeding 80 dB, which is much smaller than those due to wire breaks [1]. No typical signal that is associated with the presence of any crack was found during the monitoring. Through the comprehensive evaluation, it is safe to conclude that this bridge has no serious damage, is safe, and is in good working condition.

Conclusions

In this paper, AE and WIM systems are introduced to monitor an existing concrete bridge. It combines AE signals with vehicle load to give the correlation analysis, which verified that AE signals have a good correlation with vehicle loads. Since the WIM system can weigh passing vehicles accurately, it is helpful to identify the signals induced by different kinds of vehicles. AE signals induced by different kind vehicles are presented and the characteristics of different positions of box girder during vehicles passing the bridge are discussed. The correlation analysis indicates that this concrete bridge is in good and safe condition, having no damage or other obvious defects. Acoustic emission is an effective technique to monitor existing bridges; it is a promising technology for structure health monitoring and comprehensive evaluation of existing bridges.

Acknowledgment

The work described in this paper was partially supported by the Foundation for the Author of National Excellent Doctoral Dissertation of the P.R. China (Grant No. 2007B49), the Special Fund for Basic Scientific Research of Central Colleges of the P.R. China, Chang’an University (No. CHD2012ZD008), the Shaanxi Province Transportation Technology Research Projects (Grant No. 07-04k), and the China West Transportation Development Research Projects (Grant No. 200831849404, 20113185191410).

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