Structural health monitoring of bridges using acoustic emission technology

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Abstract—**Bridges are important part of society's infrastructure and reliable methods are necessary to monitor them and ensure their safety and efficiency. Bridges deteriorate with age and early detection of damage helps in prolonging the lives and prevent catastrophic failures. Most bridges still in used today were built decades ago and are now subjected to changes in load patterns, which can cause localized distress and if not corrected can result in bridge failure. In the past, monitoring of structures was usually done by means of visual inspection and tapping of the structures using a small hammer. Recent advancements of sensors and information technologies have resulted in new ways of monitoring the performance of structures. This paper briefly describes the current technologies used in bridge structures condition monitoring with its prime focus in the application of acoustic emission (AE) technology in the monitoring of bridge structures and its challenges.**

Keywords- Acoustic Emission, Bridge Structures, Piezo-ceramics, Wavelet

I. INTRODUCTION

Structural health monitoring (SHM) refers to the procedure used to assess the condition of structures so that their performance can be monitored and any damage can be detected early, thus increasing reliability, safety and efficiency of the structures. The process of SHM typically involves monitoring of a structure over a period of time using appropriate sensors, the extraction of damage sensitive features from the measurements given by the sensors and the analysis of these features to determine the current state of the structure [1].

Bridges are important part of society's infrastructure. Loss of lives and huge financial losses have been caused by bridge failures, as seen in the Mississippi river bridge collapse in USA in August 2007. Bridges deteriorate with age and early detection of damage helps in prolonging the lives. Several bridges built decades ago are now subjected to changes in load patterns, which can cause localized distress and if not corrected can result in bridge failure. In Queensland alone, there are nearly 3000 bridges with an annual maintenance cost in excess of 20 million dollars and a replacement value of two billion dollars. Past statistics have revealed that around 41 percent of the USA's 577,710 bridges are either structurally deficient or functionally obsolete [2]. An effective monitoring system is therefore necessary to ensure bridge safety. A lot of current research all around the globe is aimed at finding new technologies and improving existing ones.

Nowadays, various new techniques which do not depend on human's interpretation skills are available. In global monitoring techniques, damage to a structure is assessed by measuring changes in the global properties (such as mass, stiffness and damping) of the structure [3]. These techniques involve the identification of resonant frequencies shift or changes in structural mode shape [4]. Occasionally, some damage generates negligible change in dynamic properties and may go unnoticed. While the vibration based global methods can indicate the presence of damage in a structure, local methods are necessary for finding the exact location of the damage. Several non-destructive techniques are available for local structural health monitoring. Most commonly used non-destructive techniques are based on the use of mechanical waves (ultrasonic and acoustic), electromagnetic waves (magnetic testing, eddy current testing, and radiographic testing) and fiber optics [3, 5]. Fiber optics can detect various parameters change in bridges; they are normally used to sense displacement and temperature. Sensing is based on intensity, wavelength and interference of the light waves [6]. The advantages of fiber optics include geometric conformity and capability for sensing a variety of perturbations and no electric interference. However, they are very costly and required highly trained professional for the placement and construction of the system. Recently, much attention has been focus on the application of acoustic emission (AE) technology for bridge structures health monitoring. AE waves are stress waves that arise from the rapid release of strain energy that follows micro structural changes in a material [7]. Common AE sources of are initiation/growth of cracks, yielding, failure of bonds, fiber failure and de-lamination in composites. AE waves are recorded by means of sensors placed on the surface. The sensors are constructed with piezoelectric elements which convert mechanical waves into electrical signals. Analysis of these signals provides information about the source of the emission. They are highly sensitive and have the ability to locate the source initiation. It is classified as passive technique and can be used for real time monitoring.

Other non-intrusive techniques include ultrasonic, magnetic particle testing, eddy current testing and radiographic testing. In ultrasonic testing the geometric shape of a defect can be detected using an artificial signal source and response is received to identify the source [8]. This enables the position of flaw to be determined, but is expensive and the sensor can be problematic. Magnetic particle testing uses powder to detect leakage of magnetic flux [2]. Although it is relatively inexpensive compared with AE technology and ultrasonic, it cannot be used for nonferrous materials. Eddy current testing detects changes of the current patterns due to the presence of a flaw [3]. It main advantage includes ability to detect crack through paint and is effective for detecting cracks in welded joints. Unfortunately, the set up is very expensive and confined to laboratory situations.

From the above review it can be seen that acoustic emission technology offers several advantages over other methods and by virtue of these, it has become an attractive means for monitoring structures. Study of AE started in 1950s and from 1960s onwards it has been used for monitoring pressure vessels and aerospace structures. Gradually, its uses in monitoring bridge structures rose and engineers and researchers started concentrating their efforts in making AE technology more reliable and in overcoming existing drawbacks. Rapid increase in computing resources and development of sensor technology have aided in this development. This paper provides a brief review of some of the commonly used techniques for health monitoring of bridges using AE technology. Acoustic emission, a powerful technology with rapidly increasing use, is also discussed with focus on some of its past applications and challenges faced in implementation. It will also include some of the basic properties of piezoelectric elements commonly used in the construction of AE sensors.

II. APPLICATION OF AE TECHNOLOGY FOR BRIDGE MONITORING

Application of AE technology for monitoring bridges has been an active field of study. Unfortunately most of the work to date is based on computer modeling or laboratory experiments. A general overview of applications of AE for monitoring bridges has been given in [9]. Ohtsu [10] has discussed the history and development of acoustic emission in concrete engineering. Steel and concrete are two commonly used materials for building bridges and studies have mainly focused on specimen made of the two materials. Some of the previous studies on bridge monitoring using AE technology and their findings and observations are discussed next based on the nature of materials tested.

A. AE Technology in Steel Bridge Structures

Maji et al. [11] performed AE tests initially on steel beams and plates and then on real bridge. Location of AE events was based on the arrival of Lamb wave modes (extensional mode that appears as higher-velocity but with lower-amplitude waves preceding the flexural mode) at a transducer. Fast Fourier transform (FFT) was performed to identify peak frequencies and requires high pass and low pass filtering to collect the desired signal waves. It was noticed that with passing traffic and rubbing of the bridge components produced AE signals. These signals can have frequency as high as 500 kHz. Modal method was found not worthwhile for local monitoring with distances less than 1 m. Sison et al. [12] studied AE in steel bridge hanger with known fatigue cracks by recording and analyzing full waveform to obtain an in-depth knowledge of noise and crack related acoustic emission. Due to its high propagation frequencies, the amplitudes of the signal are generally very low in comparison to the background noise. Background noise was identified as the main drawback behind successful implementation. They identified that crack growth can be characterized by short rise times and long durations. Holford et al. [13] performed tests on steel bridges using Lamb wave theory to find source location. High pass and low pass filters were applied to the source waveform and the arrival times of different frequency components were recorded. They also pointed out that waveform acquisition settings must ensure capture of the first arrival of both modes and acquisition sample rate must satisfy the Nyquist criterion for the upper frequency limit of the high pass filter.

B. AE Technology in Concrete Structures

Colombo et al. [14] studied AE in concrete structures and exploring the use of AE energy as an effective parameter to quantitatively evaluate the damage. Based on the Kaiser effect, relaxation ratio was defined as average energy during unloading phase to average energy during loading phase. The relaxation ratio of greater than 1 indicates serious damage. Shigeshi et al. [15] analyzed AE emission in reinforced concrete (RC) bridges by studying the hits and energy (measured area under rectified signal envelope). Yuyama et al. [16] analyzed high-strength tendon of prestressed concrete bridges and found that analysis of detected AE signal parameters such as amplitude allowed distinguishing meaningful AE events from the failures from other sources as traffic noises.

C. AE Technology in Other Applications

Rizzo and di Scalea [17] performed tests on carbon-fiber-reinforced-polymer bridge stay cables by recording the counts, amplitudes and energy of the acoustic emission signal. Amplitude values and frequency components of the AE events were found to provide a qualitative correlation with the type of occurred damage. They suggested that optimum care needs to be practiced to understand the wave attenuation and dispersion, and highlighted that even large signals may not be recorded if source of AE is far away from the sensors. Gostautas et al. [18] tested AE on glass fiber-reinforced composites bridge decks by comparison and intensity analysis by exploring the Kaiser and the Felicity effects. Felicity ratio (FR) was defined as load at which AE events are first generated upon reloading to previously apply maximum load. Melbourne and Tomor [19] studied masonry arch barrels using AE technology and found it is effective in locating damaged regions and predicting potential areas of failure.

III. CHARACTERISTICS OF PIEZOCERAMICS

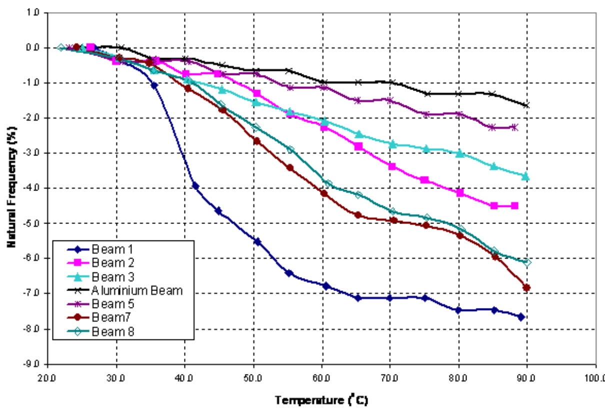
Piezoelectric materials such as Lead Zirconate Titanate ceramics (PZT) are an electromechanical material which has a complex coupling between the electrical and mechanical properties. Temperature can dramatically affect these element properties both electrically and mechanically. Additionally, material properties can vary significantly with temperature.

A. *Experimental tests*

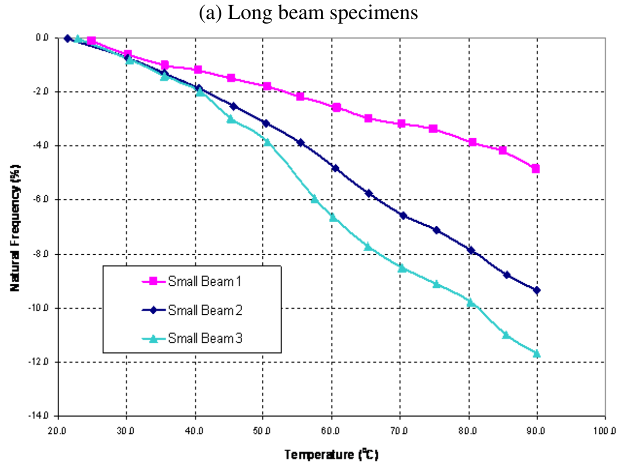
In this investigation, a number of flexible cantilever beam specimens of varying properties were studied. Specimens consisted of a series of long and short aluminum beams, as well as different types and sizes of PZT actuators and sensors adhered at their clamped ends. Additionally, different types of adhesive used to bond the PZT ceramics to the substructure are investigated.

B. *Natural Frequency*

The free-vibration test results of all beams were examined to determine the variation of the natural frequency with temperature. Fig. 1 shows the percentage deviation of the first natural frequency of the beams with temperature relative to the ambient laboratory temperature (26°C). The general trend evident in Fig 1 is that the systems natural frequency decreases as the temperature increases. This decrease is likely due to reductions in material stiffness as temperature increases. Fig. 1 shows the aluminum beams natural frequency drops relatively linearly with increasing temperature. This can be explained from the change in elasticity of aluminum which varies roughly linearly with temperature for the range considered here and the adhesive used to attached the sensors.



(a) Long beam specimens

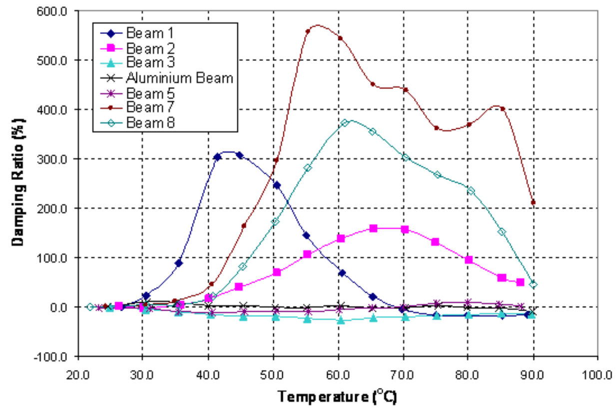


(b) Short beam specimens

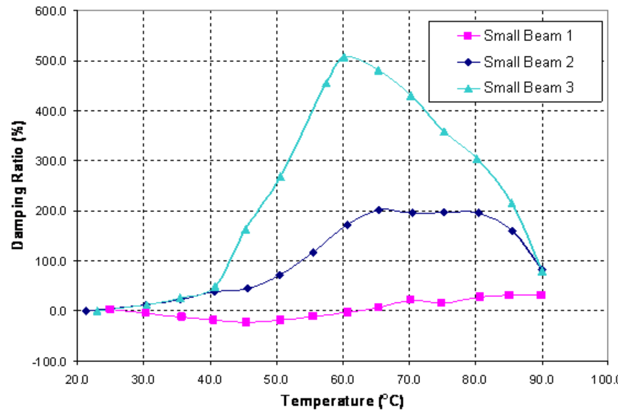
Figure 2 Percentage deviation in first natural frequency of beam specimens with temperature [20]

C. *Intrinsic Damping*

The damping characteristics of the beam specimens are considered with respect to their temperature. The damping ratio was calculated from the time histories using logarithmic decrement. Fig. 2 shows the percentage deviation of the calculated free vibration damping ratio of each individual beam with temperature. The percentage variation of the damping ratio is referenced from the individual beams room temperature



(a) Long beam specimens



(b) Short beam specimens

Figure 1 Percentage deviation in free-vibration damping ratio with temperature [20]

damping ratio.

IV. CHALLENGES

As seen in previous section, AE technology has been successfully applied for bridge structures made of steel, concrete and polymers; as well as for masonry structures. But several limitations of AE technology still exist and need further consideration. Some commonly encountered challenges can be categorised as follows.

A. *Noise suppression*

AE signals in bridge structures are often masked by noise, arising from traffic or other environment sources as well as from rubbing and movement of bridge parts. Discrimination between signal and noise is important to obtain accurate results from the tests. Some of the methods for noise suppression include high-pass frequency filtering (removes low frequency noise), signal threshold filtering (remove low amplitude noise), spatial filtering using guard sensors and analysis of signal characteristics [21]. Wavelet techniques have also been suggested to enhance signal-noise ratio (SNR). Wavelet based filter techniques have proved better alternative to traditional Fourier based filter techniques [4, 8, 22]. Hilbert-Huang transform is another method that could be used for increasing the SNR. A comparison of Fourier, wavelet and HHT is given in [4, 23]. Li and Ou [24] use relationship between rise time and duration time as a way of identifying valid AE signals. They also present differences in amplitude, duration time, rise time and frequency ranges as effective ways to differentiate between noise, continuous AE waveform and burst AE waveform. They then used filter and floating threshold by placing a guard on the sensor as ways to remove ambient noise. Sison et al. [12] stated that mechanical and fretting noises are easily distinguishable from crack-related AEs because of lower frequency contents and much longer rise times and durations.

B. Practical issues

Bridges are usually large in size, have complex shapes and composed of different materials. The number of sensors is limited by the available channels in signal analysis systems, access to bridge locations or because of economic reasons. Therefore, careful selection of regions of structures where flaws are likely to occur is necessary. Good coupling is necessary between the sensors and the test specimen to ensure signals are transmitted properly.

C. Sensor Selection and placement

Selection and optimal placement of sensors are both important for effective monitoring. Waves attenuate as they travel through the interface components and these places a limit on the distance where the sensors need to be placed. Basically there are two types of AE sensors: broad-band and resonant type. Broad-band sensors have low sensitivity but effective in broad frequency regions and may record additional background noise [25]. Resonant sensors are only effective in higher resonant frequencies and normally operate above the background noise. A solution is to use broad-band sensor for initial tests in sample specimen, and using this frequency response to select resonant sensor. Sison et al. [12] recommend the use of wideband AE sensors rather than resonant sensors for bridge testing, as the former are more capable of distinguishing between different AE sources.

D. Source localization

Finding the location of the source of damage is an important part of the monitoring process. Time of arrival (TOA) method has been a common method of determining the source location of AE waves. For this to work, several sensors are placed on a structure and the origin of the source is identified by comparing the arrival times of the signals at the sensors [9, 26, 27]. TOA method can also lead to error in source location, if there are discontinuities in the waves. Using different modes or different frequency components at the sensors may results in arrival times being calculated on wave components that have travelled at different velocities and this will lead to source location errors [28]. Three dimensional source localization presents added complicity.

Application of Lamb waves in source localization is increasingly being used lately. Lamb wave propagation phenomenon may be significant if the distances between acoustic emission source and sensors are more than about a meter [11]. Lamb waves consist of an extensional mode that often appears as a higher-velocity but lower-amplitude waves preceding the flexural mode [11, 29]. Recording the arrival time of the modes and using their velocities, a single sensor could be used to find the location of the source. For structures with complex geometric shape, both modal source location technique and TOA method are not effective. Newer source location methods have been proposed, for example a method based on AE energy has been discussed in [26] and a method based on grid of time differences is used by [30].

E. Data management

AE monitoring methods can be classified as either parameter-based or signal-based [8]. Parameter-based monitoring is the traditional approach, where only some of the parameters of the signals, such as amplitude, number of hits, signal duration and rise time are recorded and rest of the signal is discarded. With higher computing resources available, it is now possible to record the whole waveform and this constitutes the signal-based approach. It may also be necessary to continuously monitor a structure for a long period of time. This will generate a large amount of data and effective storage and management of data is necessary to establish effective health monitoring system. Wireless sensing of structures offers added benefits and new techniques are being investigated [31].

V. CONCLUSIONS

This paper has provided a brief introduction to various SHM methods available for testing of bridges. Bridges are important part of society's infrastructure and reliable methods are necessary to monitor them and ensure their safety and efficiency. Acoustic emission technology has proven to be a suitable method for this purpose and possesses several distinct advantages over other monitoring methods. Previous successful applications have established AE as a viable technique for testing steel, concrete and other materials commonly used in bridge structures.

Although the use of AE as health monitoring tool for bridges is growing rapidly, limitations still exist. Some of the common limitations were discussed in this paper. Further research is necessary to alleviate them and develop an effective AE monitoring system. Literature review has identified the presence of noises as one of the main problems, so denoising signals can be identified as a major challenge. Signal conditioning of AE data obtained from bridge structure monitoring, using methods such as Wavelets and Hilbert-Huang, can be identified as the future direction of work.

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