AUSTRALIAN NETWORK OF STRUCTURAL HEALTH MONITORING

Newsletter

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Contents

President Report 1
Damage Identification in the Concrete Jack Arche Bridge Using Spectral Moments 8
A Technical Note on: Guided Wave Based Damage Evaluation in Pipelines 17
Photo Gallery of VicRoads/ANSHM Technical Workshop 22
Conference News 27

President Message

Tommy Chan

Professor in Civil Engineering, Queensland University of Technology

Dear All,

The most shocking and sad news that we received in August should be the collapse of the Morandi Bridge in Italy on 14th of August 2018, killing 43 people. The construction of the Morandi Bridge was started in 1963 and completed in 1967. Some put the blame to the designer of the bridge. Actually, the Morandi Bridge could be considered to be a new type of bridges at its time. The first modern cable-stayed bridge was the Strömsund Bridge in Sweden of which the construction was completed in 1955. It could be seen that the Strömsund Bridge looks very similar to the Morandi Bridge with only a few cables at each side. Then it comes to the Theodor-Reuss Bridge in Germany which was completed in 1957. It is considered to be the first cable-stayed bridge with Harp pattern cables as compared with Fan pattern cables for the earlier cable-stayed bridges. It could also be seen that the Theodor-Reuss Bridge consisted of not many cables as the cable-stayed bridges nowadays. In the Morandi Bridge it was tried to be "innovative", so only one cable at each side of the tower embedded inside concrete. Did the bridge perform as what it was expected in the design?

Also, according to the news media, the bridge has been under constant monitoring and maintenance works. However, it still experienced a catastrophic collapse. Were such works effective? The main issue is whether such inspection, monitoring and assessment could provide sufficient and timely information to the maintenance team for them to carry out adequate maintenance.

FIU Bridge was collapsed during the time some construction activities were undergoing. Similarly, the collapse of the Morandi Bridge was during the time when some maintenance work was carrying out. The maintenance activities were stopped at the time of collapse because of a serious storm was attacking the area. Although the causes for the collapses of both bridges have not been reported, I am sure that if both bridges were installed with a SHM system to give real-time "as-is" conditions of the structure, the accidents could be avoided, and lives could be saved.

No timely decision could be made if no real time "as-is" condition information could be provided. As it was mentioned in the recent ATCSHM Brisbane Workshop that nowadays for a normal car, there are a lot of sensors installed in the car. There are no such systems for more expensive structures like bridges. It all prompts the need to promote and develop SHM technologies so that it will become mandatory to install various levels of SHM system on bridges.

In my monthly updates on 30 March 2018, I mentioned that the collapsed FIU bridge used a new material, using self-cleaning concrete and a new construction method, adopting the so-called ABC (Accelerated Bridge Construction) technology. The Morandi Bridge was also a new design at its time. For new materials, new design structural systems and new construction methods, we also need to know better their actual behaviour and performance in both short and long terms. With SHM systems installed in structures using new materials, new design structural systems and new construction methods, the performance information could be provided to help understand better the behaviour of these new systems which could not only enhance its safety as early as during its construction, but also provide "as-future" information to validate the design assumptions as well as to improve future design.

After the collapse of the Morandi Bridge, I have been interviewed by news media a number of times. A similar question was asked in these interviews, "Is it safe to travel across bridges in Australia?" Whenever a structure collapses, the public lost their trust to engineers. I am proud to be a structural engineer. However, whenever there is a structural collapse, we lost our image. We build a bridge structure that will last for 100 years, but we also need to admit the fact that a structure may have deterioration and damage that will affect the performance of the structure throughout its life span. At the same time bridges are also required to sustain the loadings which are more than those at its time of design. Such increase should have been allowed in a proper design standard within its design life span. The question is how about bridges when its design life has lapsed or close to its "expiry date", the end of its design life. Effective maintenance of the bridge structures using SHM could help extend the life span and enhance its safety. It could be demonstrated that with SHM technologies, there will be a reduction of more than 30% of the replacing costs to deal with this kind of bridges.

According to *Corriere della Sera* (an Italian daily Newsletter, 14 Aug 2018) this was the 11th bridge collapse in Italy since 2013. Italian bridges are ageing but with the loading being increased because of the request of the freight industry. Australia is facing a similar situation. Should we need to help the public and the authorities to seriously consider the importance of SHM? Colin has written a very good article using the collapse of the Morandi Bridge to promote SHM
(http://www.abc.net.au/news/2018-08-17/genoa-bridge-collapse-road-safety-ponte-morandi-west-gate/10131098)

It is not difficult to formulate a business case for SHM. However, we should also bear in mind about we should not only look at the Hard Benefits, benefits that can be economically quantified and assigned financial values. We should also consider the Soft Benefits, the benefits that are intangible and could not be readily assigned specific financial values but it could help save costs or avoid paying a price. Just looking at the collapse of the Morandi Bridge, how much for the cost of families lost their beloved ones, engineers lost their image, public lost their trust in using infrastructures, connection lost between two places, productivity lost, etc.

It is interesting to notice that whenever there is a significant earthquake happened killing lots of people and damaging infrastructures, the government will provide more funding for research and development on seismic studies. However, it is not the case for fatal collapses of infrastructures. It seems that SHM is such an important technology which should have been treated at least on par with other technologies. To me, I could consider the collapse of the FIU bridge and the Morandi bridge could be avoided if SHM has been implemented to both of them. Not sure how many more of this kind of accidents need to happen before the authorities could realise the importance of SHM and provide more funding to research, develop and implement SHM technologies to avoid this kind of tragedies to happen again. Our proposal of establishing ANSHM ARC ITTC on SHM is timely!

Below are two links for those who are interested to listen to some of my interviews to discuss the collapse of the Morandi Bridge:
https://soundcloud.com/abc-southern-qld/how-safe-are-our-bridges
https://2ser.com/what-caused-the-bridge-collapse-in-genoa/.

Below are the updates of the month.

ITRP Proposal Preparation

Change of Title of our ANSHM ARC ITTC
As mentioned earlier, in order to have our ITRP proposal to have a better chance of success, we need to have our proposal objectives to be aligned with one or more of the priorities for the six high-growth sectors established under the Industry Growth Centres initiative:

- Advanced Manufacturing
- Cyber Security
- Food and Agribusiness
- Medical Technologies and Pharmaceuticals
- Mining Equipment, Technology and Services
- Oil, Gas and Energy Resources.

In the early August, we had two important meetings related to our ITTC. One was with Mr Mark Peters, the State Director (QLD, NT) of Advanced Manufacturing Growth Centre (AMGC) and the other one was the ANSHM ARC ITTC Task Force Subcommittee meeting.
Mark basically agreed the significance of our centre but he would like to see clearly how the centre could be beneficial to advanced manufacturing industry. However, based on the experience gained on the success of other

ITTC proposals, we consider that although aligning with an identified priority is important, yet it does not have to have the aim of our proposed ITTC to be fully aligned with advanced manufacturing. Mark also reminded us about the importance of applying SHM to mining as "Mining Equipment, Technology and Services" is another identified priority. Likewise, applying SHM to pipelines may also help us to align with another area since "Oil, Gas and Energy Resources" is the third identified priority that we could work on. Therefore, if we have some IPs from mining and oil and gas industries, it will make our proposal even stronger.

Therefore, we decide to set the aim of our ITTC as follows with two foci:

The aim of this ITTC is to use SHM to collect data on infrastructure performance and use this new knowledge to manufacture improved and innovative materials/components for energy infrastructure (pipelines, oil platforms, wind turbines, cooling towers, mining railroads) and civil infrastructure (bridges, roads, tunnels, buildings including modular buildings) and innovative sensors in addition to the use of SHM for the efficient operation and safety of our infrastructure.

In this way we could broaden our potential industry partners and later we could fine tune the scope to eliminate those we could not have any industry partners.

Regarding the title of the training centre, the original title of "ARC Training Centre for Infrastructure Safety and Operations" needs to be revised as well to highlight more with SHM. The revised title now is ARC Training Centre for Innovative SHM Technologies for Advanced Manufacturing and Infrastructure Safety and Operations (ATCSHM). ATCSHM could also help people to relate this centre as ANSHM ARC ITTC on SHM, for those who are familiar with the acronyms of ANSHM, ARC, ITTC and SHM.

Hope this change of our proposed title will not cause much confusion. For those who have experience in preparing ARC proposals, they may have to change their titles a number of times before their final submission.

We have also revised accordingly the *Call for Participation from Industry Partners* flyer for this change of title and aim.

As mentioned earlier that for ANSHM members who are affiliated with other universities, you can participate this ITTC as non-CI. You can also join it as a CI, if you can secure cash contribution from the Industry Partners. Please contact me and let me know your plan. Please also email me if you would like to have a soft copy of the revised *Call for Participation from Industry Partners* flyer.

2nd ANSHM ARC ITTC Workshop, Brisbane

The 2nd ANSHM ARC ITTC Workshop for ATCSHM had been held on 21 August 2018 at Queensland University of Technology (QUT) in Brisbane. It was as successful as the one in Melbourne. We have around 30 attendees with representatives from QUT, ARRB, ARUP, Bentley Systems, Brisbane City Council, Griffith U, Heywood Engineering, Monitum, Multinail, Rocktech, Queensland Department of Agriculture and Fisheries, Queensland Department of Transport and Main Roads, Transurban, U of Melbourne, USQ. The main objectives of that workshop were to help various government organizations and companies better understand the Industry Transformation Training Centre (ITTC) under the Australian Research Council Industry Transform Research Program (ARC ITRP) scheme and see how they can get involved in the ITTC on SHM. The five speakers from the industry presented their challenges and what are the benefits that they could get from joining this ITTC and what are the tasks that they would like this ITTC to work for them. The discussion in the Open Discussion session was extremely useful and it helped clarify other companies/organizations about the benefits of joining this ITTC and how they could participate.

Below are some photos taken during this Brisbane ATCSHM Workshop and other photos are shown in the Photo Gallery of this issue.

We have audio and video recordings of this Workshop including the desktop screenshot of each presentation. For those who would like to watch or listen to the recordings, please email me and I will send you the link to download the recordings.

Please note that we are going to organise another ANSHM ARC ITTC Workshop in Sydney. Jianchun will give you more details in due course.

ANSHM Page (www.ANSHM.org.au)

As mentioned in the last monthly updates that the VicRoads-ANSHM Technical Workshop was very successful, and the presentations were well received. I am so pleased to inform you that the Workshop slides have been uploaded to ANSHM website. Thank Colin, Hong, Xinqun for their prompt actions in making these slides available so soon.

ANSHM 10th Annual Workshop

I am pleased to inform you that the tentative date for the 10th ANSHM Workshop at U of Wollongong has been scheduled from 10-12 Dec 2018. It will be held in parallel with IAPS Australian Workshop. To follow our tradition, the first two days will be for ANSHM/IAPS Workshops and the last day (12 Dec 2018) will be an optional lab tour of NFPBS. The detailed information will be released by the organisers soon later. Please lock the dates in your calendar and more information will be announced in due course.

ANSHM Special Issues

ANSHM Second Special Issue in SHMIJ

As mentioned in the last monthly updates, we have received 16 papers for review. The status of the papers are as follows:

6 with final acceptance;
2 were rejected;
5 are under 2nd review round; and
3 with authors for revision after 1st review.

It seems that we are unlikely to have this special issue to be published in September. However, we are still trying our best to publish this SI as soon as possible. Thank you for those who have accepted the review invitation. Please return the review report by the deadline. For those who are revising your papers, please also complete your revision by the deadlines required.

ANSHM 3rd Special Issue in CSHM

Thirteen papers have been received for review and eleven have been accepted and included in this special issue, after a rigorous peer-review process. The preface has also been submitted. I should thank Colin and Jun for co-editing this special issue with me. Actually, they have done most of the work and we should thank them so much for their service to ANSHM.

ANSHM Special Sessions in ACMSM25

We have received 8 papers for this Special Session. The review process has completed, and all the revised paper have arrived. Thank so much the authors and reviewers for your timely actions.

SHMII-8 Follow Up Work

As mentioned earlier, Saeed and I will co-edit a special issue in CSHM for the best paper nominee. We have received 7 papers in total submitting to this special issue with two papers receiving review comments as 'Major Revisions' and the other five are still under review. We have also another paper which supposed to be submitted to this SI but is handling by another editor due to a mistake. It will be included in this special issue if it is accepted for publication.

The ANSHM Newsletter

As discussed in the Industry Forum at our last ANSHM Workshop we may include some technical notes on SHM to help the industry to better understand some of the SHM technologies. It can be seen that we have included a technical note in this issue. We hope starting from this issue, we will include a technical note in our Newsletter. In this issue Guan and Lu write a technical note on the use of guided waves for SHM to better understand the background and some guidelines in using this technique for damage evaluation in pipelines. This could help those who are not familiar with this technique to understand this technique better. Besides, Alamdari (Mehri) et al also presented a non-model-based damage identification method based on the concept of structural moments using output only response.

Thank Mehri and other Editorial Team members Jun and Andy for preparing this newsletter.

With kind regards,
Tommy Chan
President, ANSHM
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Damage Identification in the Concrete Jack Arche Bridge Using Spectral Moments

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Introduction

Statistical time series-based structural health monitoring (SHM) is a well-known technique that has been used by several researchers to identify structural damage by utilizing statistical models and identification techniques (Makki Alamdari et al. 2014; Makki Alamdari et al. 2015; Labuz et al. 2011). There are two stages in this method: first, training phase, in which a continuum of damage states considering different locations and magnitudes is stochastically modelled. Each damage topology corresponds to a specific pattern and represented by a feature vector. Features represent the underlying structural physics of the system and statistical boundary construction between two features is crucial in effectiveness of this algorithm. Several autoregressive-based feature extraction methods have been introduced and adopted in previous works (Lu & Gao 2005; Roy et al. 2015). The second phase in statistical time series-based SHM is the inspection phase which compares the current unknown state of the structure with pre-determined stochastic models to identify any possible damage in a statistical decision-making framework. Some researchers have defined a class of features developed based on generic phase space (J.M. 2003). They used phase space representations of the system to predict the future response. The predicted response is then compared with the observed data to make decision on any possible damage occurrence.

Besides statistical-based approaches, spectral methods in the frequency domain have become another alternative to extract features in mechanical components under stochastic loadings. Application of spectral methods in the context of damage detection has been found in the literature (Antoni and Randall 2006, Herve et al. 2015). Spectral methods work based on the spectral moments which can be evaluated directly from the power spectral density (PSD) of time responses. Spectral moments represent some major statistical properties of a stochastic process; for example, the variance of a random process is the zero-order spectral moment of that observation. Spectral moments are useful for characterization of non-Gaussian signals buried in

Gaussian background such as noisy environment. To the best knowledge of the authors, the early efforts in this field were conducted by Vanmarcke (Vanmarcke 1977; Der Kiureghian 1980) to estimate modal parameters (natural frequency and damping) from ambient response measurements of dynamically excited structures. Zero, first and second moments were applied to identify modal parameters. Later on, some researchers used spectral moments to predict the fatigue damage evaluation and estimate the rate of damage accumulation in structures subjected to random processes (Benasciutti et al. 2013; Larsen & Irvine 2015). Several researchers applied higher order spectral moments such as spectral kurtosis (SK) of the time series data for health assessment of rotary structures (Antoni & Randall 2006).

This work is part of the efforts which have applied SHM to the Sydney Harbor Bridge. In this study, a spectral-based method is used in the prediction of cracking in steel reinforced concrete structures. A Damage Index (DI) was defined based on the change in the spectral moment calculated from a baseline state and un-known state of the structure. Field test data from the Sydney Harbor Bridge are implemented for testing and verification of the method.

Methodology

Power Spectral Density (PSD) is an important physical quantity of a stationary random process and, since it is easily accessible experimentally, it is widely used to extract features from temporal and spatial random signals in various applications. PSD reduces the redundancy in signals by concentrating its information into smaller areas of the frequency domain. Although, PSD highlights the information-rich part of the signal, it still contains significant amount of data which is not convenient to be directly applied for the feature extraction. Hence, further data reduction is required to characterize PSD in an efficient way. In this regard, spectral moments have been introduced and implemented in many cases of engineering interest to analyse systems subject to stationary random processes such as analysing ocean waves, image processing, vocal analysis, fatigue failure prediction, etc. (Lutes & Larsen 1990; Caddemi et al. 2004).

For a given PSD, the nth-order spectral moment for sensor location i, can be expressed by,

$$\lambda_{x_i}^{n} = \int_{-\infty}^{+\infty} |\omega|^{n} S_{xx_i}(\omega) d\omega \tag{1}$$

where $S_{xx_i}(\omega)$ is the PSD of the response at sensor location i , and frequency ω. n is the order of spectral moment. As illustrated by Equation.1, spectral moments retrieve information directly from PSD without any further manipulation.

For a discretised signal, the *n-th* order spectral moment can be obtained by,

$$\lambda_{x_i}^n = \frac{2}{N^{n+1}} \sum_{0}^{\lfloor N/2 \rfloor} S_{xx_i}(j)\left(\frac{j}{\Delta t}\right)^n \qquad j \in [1{:}N/2] \tag{2}$$

where S_{xx_i} is the discrete N point spectral density obtained by discrete Fourier transform of auto-correlation of $x_i(t)$; Δt is the sampling period and n describes the order of spectral moment. Spectral moment can be interpreted as the sum of all frequency spectra with a weighting. Damage, based on its location, affects specific frequencies in the structure. By summing up the individual contribution of each frequency, spectral moment provides an indication of damage presence. The estimated spectral moments of the structure at current state and a baseline state are utilized to determine whether or not the structure is damaged by the following damage index

$$\delta_i^n = \left| 1 - \frac{(\lambda_{x_i}^n)_C}{(\lambda_{x_i}^n)_B} \right| \tag{3}$$

δ_i^n represents damage index for location i obtained from the *n-th* order spectral moment of two successive states of the structure. $(\lambda_{x_i}^n)_C$ and $(\lambda_{x_i}^n)_B$ are, respectively, the *n-th* spectral moments of the structure for the current state and the baseline state of the structure. It should be noted that the baseline state of the structure is not necessarily the healthy state of the structure.

In the next section, the proposed damage index is implemented to identify existing crack in a reinforced concrete jack arch in the Sydney Harbor Bridge before conducting the repair.

Field test investigation

The Sydney Harbor Bridge (SHB) was opened in 1932. It is a steel through arch bridge operated by Roads and Maritime Services (RMS) – the road authority of the state of New South Wales, Australia. The bridge carries lanes of 8-road traffic and two railway lines. Traffic lane 7 is a dedicated bus and taxi lane on the eastern side of the bridge. Lane 7 consists of an asphalt road surface on a concrete deck supported by concrete and steel jack arches. There are approximately 800 jack arches over a total distance of 1.2 km. The jack arches are difficult to

access and are inspected typically at two yearly intervals according to standard visual inspection practices. Figure.1. illustrates one single jack arch in the structure.
All the joints are similar in geometry however, depending on the location of the joint along the span, the dynamic characteristic may differ due to the change in the boundary conditions.
For the current case study, three instrumented jack arches were considered: Joint 1, Joint 4 and Joint 6. These three joints are illustrated in the schematic shown in Figure2. These joints are located on the eastern side of the bridge underneath lane 7 near the north pylon. Joints 1 to 3 are separated by an expansion joint from Joints 4 to 6. Analysed data were collected from tri-axial accelerometer mounted on the base of each joint. Each tri-axial accelerometer measures acceleration responses in the direction of passing traffic (x), in the direction of gravity (z) and in the direction of (y). These three directions have been illustrated in Figure.1. In this study, only measured responses in (z) direction is utilized. The data were collected after the vehicles, usually buses, drive over the deck where the sensors are located. A pre-set threshold was used to trigger the recording on the sensor. Each recorded data set, after triggering, is called an event which corresponds to a passing vehicle on the deck just above the joint. The data were collected during the period from August to October in 2012. During this time a known crack existed on joint 4 while all the others were in good condition. Each sensor (after it is triggered) records for a period of 1.6 seconds at a sample rate of 375 Hz resulting 600 samples. Later, Joint 4 was repaired in February 2013 and another set of data was collected on the 10th of April 2014. The data after repair were collected with a frequency sampling of 250 Hz for duration of 2 seconds resulting 500 samples.
In this case, two sets of data were available for analysis: (a) Joint 4 damaged and the rest of the joints are healthy (before repair) and (b) all the joints are healthy (after repair).

Damage Identification Results

For damage identification purpose, 200 randomly selected events were considered for each joint before and after repair. Measured time data for each event was first normalized according to the Equation.4.

$$\overline{x(t)} = \frac{x(t) - \mu}{\sigma} \tag{4}$$

where μ , σ , $x(t)$ and $\overline{x(t)}$ are, respectively, the mean value, standard deviation, the original time signal and the normalized time signal.

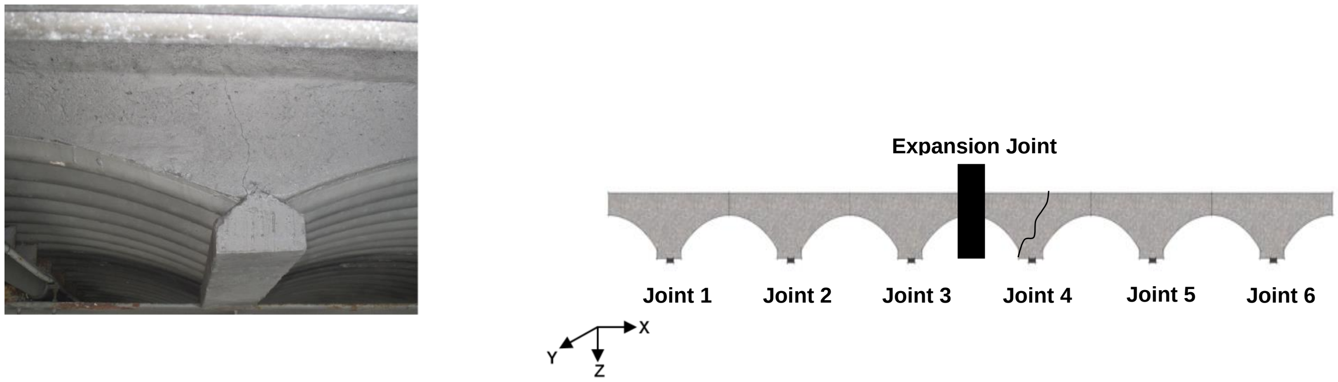
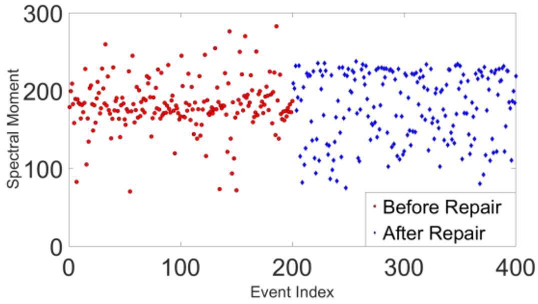


Figure 1. Illustration of one of the concrete jack arches underneath the bus lane.

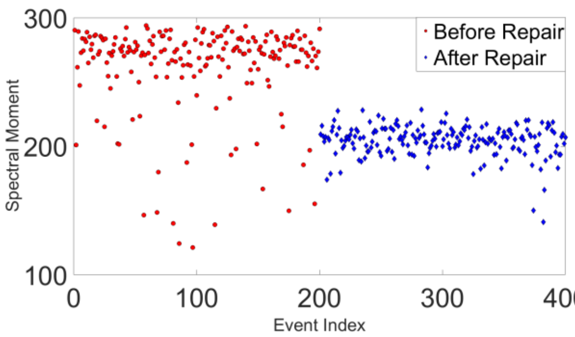
After normalization, damage identification procedure starts by generating the PSD of each event. Since the data acquisition set up, frequency sampling and number of samples, is not the same for events before and after repair, special consideration was made to make sure that the constructed PSDs, before and after repair, have the same frequency resolution and the same frequency range.

For each event, the first order spectral moment was estimated using Equation.2. The estimated spectral moments for Joints 1, 4 and 6 have been, respectively, shown in Figure.2. In these figures, the horizontal axis corresponds to the 400 events, 200 from before repair and 200 from after repair. The vertical axis shows the first order spectral moment.

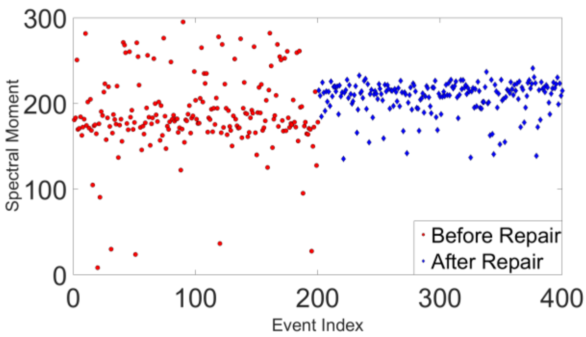
According to the Figure.2, it can be clearly seen that for damaged Joint 4, there is a considerable difference between the obtained spectral moments before and after repair compared to the ones obtained from Joints 1 and 6. For further investigation, the average of spectral moments, obtained from 200 events, was estimated for each joint, before and after repair and the results were shown in Figure.3. As illustrated in Figure.3, the average of spectral moments before and after repair is quite similar for Joint 1; the reason is simply because of the fact that this joint is not damaged and it is not located in the vicinity of damaged Joint 4 to be affected. As said earlier, Joint 1 belongs to another substructure which is separated from Joints 4 to 6 by an expansion joint. On the other hand, as expected, the maximum deviation occurs at damaged Joint 4. Moreover, a change can be seen in Joint 6, although, it is undamaged. The possible reason for this change can be the strengthening of that part of the structure after repair which affects Joint 6 as well. Another reason for this change can be the potential effect of damage on the dynamic behaviour of this joint before repair, since Joint 6 is closely located to the damaged Joint 4. The damage indices for these three joints were estimated according to Equation.3 and the result was illustrated in Figure. 4. The data after repair was considered as benchmark for all the joints. According to this figure, it can be readily realized that the damage index for Joint 4 before repair was 28% higher than the one after repair. Also, a change of 10% is visible for Joint 6 which is closely located to damage and most likely has been affected by damage and repair. On the contrary, only a slight change of 1% occurs at damage index for Joint 1 which demonstrates the fact that this joint is not influenced by damage and repair since it belongs to a separate substructure.



(a)



(b)



(c)

Figure 2. Spectral moments obtained from 200 events at (a) Joint 1, (b) Joint 4 and (c) Joint 6.

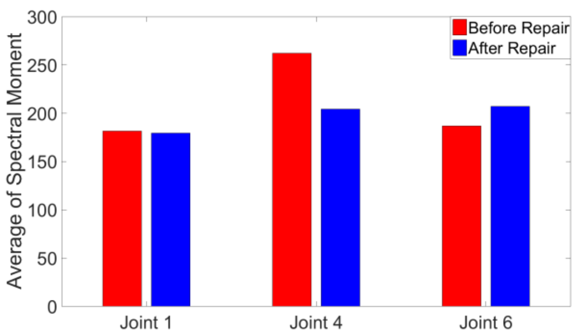


Figure 3. Average of spectral moments obtained for 200 events for joints 1, 4 and 6 before and after repair.

Conclusion

Developing non-model-based damage characterization schemes using output only response is in high demand by SHM community since this approach does not require service interruption and expensive devices to excite the structures in real-life applications. To this aim, this paper presented a damage identification method based on the concept of spectral moments. A response parameter known as spectral moment was implemented for characterization of damage. A damage index was defined by comparing the spectral moments of two successive states of the structure. The method was successfully applied on reinforced concrete jack arches which are major structural components in the Sydney Harbor Bridge. It was demonstrated that the method can reliably differentiate between the healthy joint (after repair) and damaged joint (before repair). It was also illustrated that the dynamic behaviour of joints located in the vicinity of damage are affected by damage, hence, a non-zero damage index is obtained, although, it is much smaller than the one obtained for the damaged joint. On the contrary, no noticeable damage index is obtained for joints far from damage location. Besides the promising results, the method is easy to be implemented as damage sensitive feature is a scalar parameter. Moreover, the proposed feature contains broadband frequency information from a wide frequency range. Showing promising results along with being a computationally efficient approach, the method can open an opportunity to be applied for real life SHM applications.

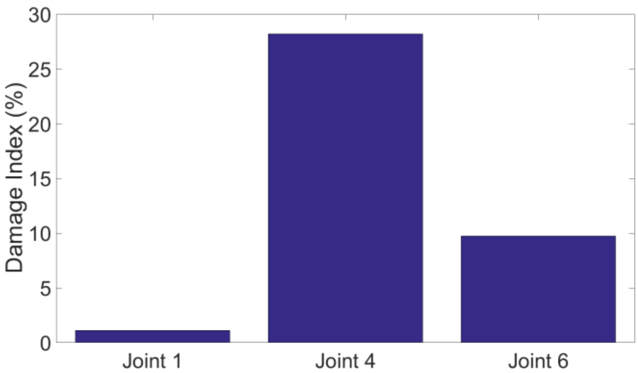


Figure 4. Comparison of damage index for Joints 1, 4 and 6.

Acknowledgement

The authors wish to thank the Road and Maritime Services (RMS) in New South Wales and Datat61|CSIRO (former National ICT Australia (NICTA)) for provision of the support and testing facilities for this research work.

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A Technical Note on: Guided Wave Based Damage Evaluation in Pipelines

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Abstract

Guided wave based approach is an attractive and cost-effective technique for pipeline inspection in comparison with conventional non-destructive evaluation (NDE). Relevant researches have been conducted comprehensively since the 1980s to detect a wide variety of types of damage in pipelines. This report introduced the damage detection principle, wave mode selection and sensor types utilised in pipe inspection and certain outstanding issues for future study.

Introduction

Guided waves are stress waves propagating within the material boundaries that guide the wave along the structure. Guided wave-based approaches have been successful in detecting various types of damage in engineering structures including civil infrastructure [1, 2]. In particular, guided wave-based approach is an attractive and cost-effective technique for pipeline inspection, since guided waves can propagate underneath coatings within a long distance and the installation of transducers for exciting and receiving waves only needs removal of a small part of insulation. The multimode guided waves can propagate along different paths including circumferential and longitudinal and through the thickness of the pipe [3]. Due to these properties, guided waves have presented potential capacity for detecting different types of damage on both the inside and outside surface of a pipe.

Guided-wave based damage detection in pipelines

When guided waves approach a discontinuity in a pipe, the wave will interact with the defect and the reflected or transmitted signal from the defect usually contains useful information related to characteristics of the defect, as indicated in Figure 1.

Many studies [4, 5] have established the relation between reflection amplitude and crack characteristics such as crack depth, circumferential and axial extent, which provide quantitative evaluation of crack in pipes. Also, the time of flight (ToF) of propagating waves can provide direct information about the location of damage in pipes [6]. Sometimes when the incident guided wave is oblique to a defect, one form of wave energy can be converted to another, known as mode conversion, which benefits pipe inspection, especially for bent pipes [7] and for some specific defect types.

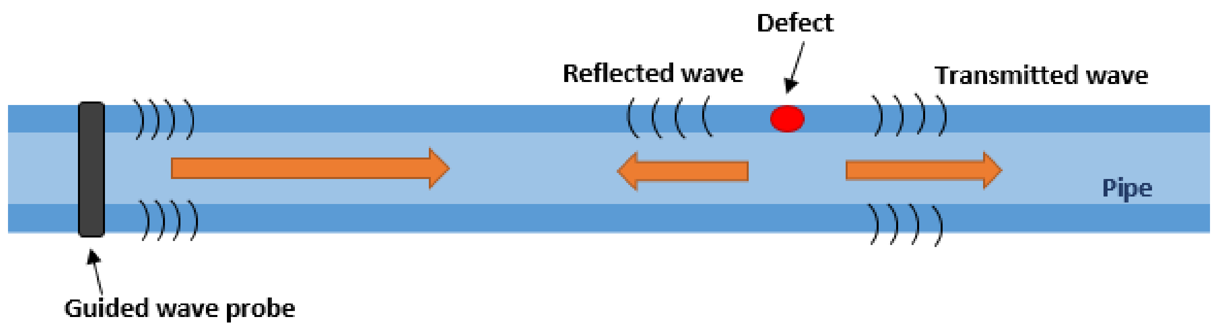

Figure 1 Principle of damage detection in pipes with guided waves

Guided wave mode selection and excitation

Due to the curvature in pipes and the dispersion characteristics, wave propagation in this type of structure is complex. In practice, axisymmetric modes, including longitudinal and torsional modes, are attractive for testing. In particular, L(0, 2) mode travels faster than the other modes and is non-dispersive within a wide range of frequencies [8]. L(0, 2) is superior to detect changes in the depth and circumference of defects [9]. Torsional mode T(0, 1) is an alternative mode to L(0, 2) and is widely analysed and applied as well [10], in particular for the detection of cracks along the axis of pipes and pipelines with coating and pipelines that carry or are buried in liquid [10].

To generate and receive guided waves, a range of ultrasonic transducers can be used, e.g. piezoelectric lead zirconate titanate (PZT) [9], angle beam transducer with a wedge, polyvinylidene fluoride film (PVDF) [11], and electromagnetic acoustic transducer (EMAT) [12]. Among these, the piezoelectric transducer and EMAT are widely used in pipe inspection. **Error! Reference source not found.**A popular setup is to arrange a ring of transducer elements symmetrically around the circumference of a pipe, so as to suppress the non-axisymmetric modes. For example, to excite axisymmetric L(0, 2) mode in pipes, the dry coupled piezoelectric transducer system has been developed, which consists several piezoelectric length-expander elements spaced equally surrounding the circumference and clamped at one end of the pipe [13]. A transducer ring system (in Figure 2) developed by Guided Ultrasonics Ltd. [14] can generate both the longitudinal and torsional guided waves [15].

Figure 2 Solid rings for wave excitation and acquisition

Outstanding issues in pipe detection

Effect of environmental and operational conditions (EOCs) always affect the propagation of guided waves, where the changes in temperature, humidity or flow rate, etc., generally mask the changes caused by structural anomalies [16]. These issues influence the operator quality of field inspection and can be improved by hardware development to increase the data quality. Further study on the effect of EOCs and techniques without baseline data is necessary for pipe inspection under changing EOCs.

Surrounding and coating materials of pipelines can also affect the wave propagation in pipes. For highly alternative coatings, the utilising of guided wave testing is quite limited. In addition, complex features such as welds and flanges which complicate wave propagation and potentially cause mode conversion. All these outstanding issues need further investigation with efficient signal interpretation approaches.

Conclusion

In this report, the fundamental properties and principles of guided waves in pipe inspection was introduced. It is understood that the reflection, transmission and mode conversion of guided waves have been widely used to identify different types of damage. Due to the dispersion and attenuation properties, selection of proper modes such as L(0, 2) and T(0, 1) modes for inspection is necessary in practice. Excitation of these wave modes using different types of sensors was also introduced. When considering the practical problems, the complex features in pipes, materials surrounding of pipes and the environmental temperature will influence the inspection quality.

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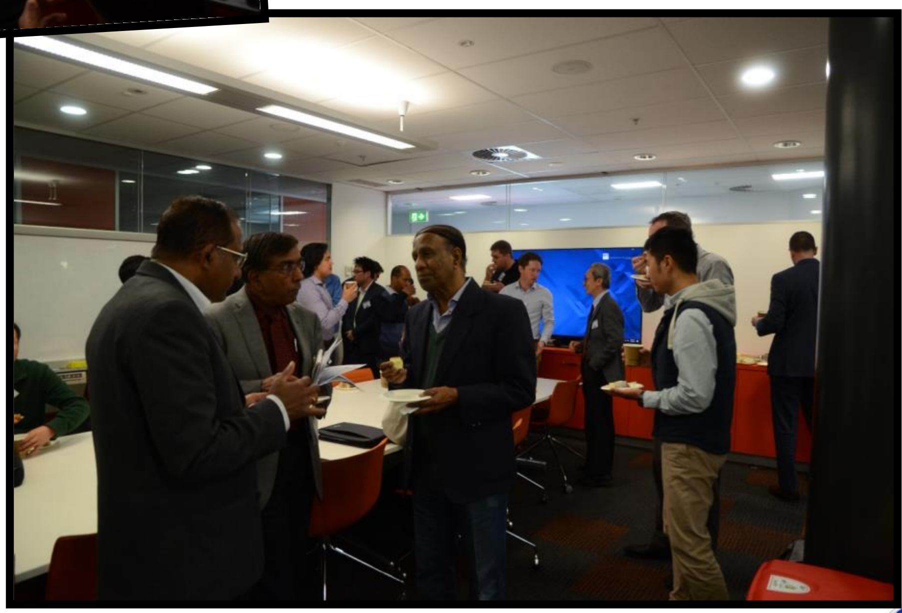

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