AUSTRALIAN NETWORK OF STRUCTURAL HEALTH MONITORING

Newsletter

CIVIL ENGINEERS ANSHM

Issue 33, September 2022

Contents

President Message

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Dear All,

In ANSHM Newsletter Issue 28, I mentioned that we were excited that the Victorian government appreciates so much the technologies of Structural Health Monitoring, as on 10 May the Victorian government announced that it would invest $50 million to develop a new technology that will remotely monitor bridges to better manage their maintenance. Although we welcome the project confirming more extensive application of SHM technologies in Australia, yet we expressed our concern that as no open and transparent bidding process in awarding the contract to a particular SHM service provider could be identified. In this regard, we prepared a letter to the relevant parties to voice out our concerns. Jenny Wiggins, Infrastructure Report of the Financial Review wrote an article about this, and it was published on 24 May 2021[1]. Because of this investment, Xerox and the

[1] https://www.afr.com/companies/infrastructure/transparency-concerns-over-xerox-linked-bridge-contract-20210521-p57tyn

Victorian Government partnered to launch Eloque, a joint venture to commercialize new technology that will remotely monitor the structural health of bridges. After a bit more than a year of the launching of Eloque, it was reported that Eloque has a plan to ramp up deployment to over 100 bridges in Australia by the end of 2022 (from Engineering.com dated 17 June 2022). We are looking forward to seeing if we could access the data collected for research purpose. However, we are then surprised to know that Eloque is retreating from Australia after 15 months of operations, which was confirmed by Mr Dusan Stojkovic, the Head of Product at Eloque.

We are not sure about the exact reason for Eloque to stop their business here after installing and planning their SHM systems to bridges in Australia. Although we have been working hard in Australia to help the engineering community to better understand what SHM is and what could be expected from SHM, I consider that many still misconceive that SHM is to install sensors on a structure to collect data, and then such a system could provide information to detect damages. As I always say, and this is not the first time I make this statement, “SHM is more than installing sensors”. We need to have the installed sensors to make sense, so we need to select the correct sensors to deploy them correctly and transmit, store and retrieve them using a correct system, and use correct methods to analyse them to provide correct information for the decision makers and the corresponding teams. We need to develop some guidelines and standards to ensure what should be expected from such a system. The application of SHM could only grow healthily if we could help the potential users of SHM understand better what they will expect to get. We, with the experts and experienced engineers in SHM are working on the ANSHM objectives to help Implement, Promote, Apply and Develop SHM technologies to help the asset owners to better understand the SHM technologies in Australia. We are happy and impartial to provide our expert advice to help the potential users of SHM, including various Local, State, and Federal governments to find the best solution and the best choice for their problems related to SHM.

We, the ANSHM Executive Committee, had a detailed discussion on the closing of Eloque in a recent EC meeting. Besides, you may be interested to read a media report[2] to discuss untransparent funding process from the Victorian State Government when Neil Mitchell interviewed John Vazey, our ANSHM Industry Liaison Officer. A/Prof Colin Caprani, our ANSHM Executive Committee member also submitted the pitch to The Conversation to draw more attention from the peer and public about the issue. Besides, Dr Yew-chin Koay, also considers that it is the time for us to alert the Government better the importance of ANSHM to educate and work closely with the Government.

[2] https://www.3aw.com.au/state-government-poured-16m-into-venture-it-was-warned-would-fail/

This is also the reason that we would like to establish an ARC Industry Transformation Training Centre to train new generation of professionals to meet the demands of this important sector because of the emerging realisation of the SHM technologies. Hence, we submitted an application for ARC funding for the proposed ATCSHM (ARC Training Centre for Structural Health Monitoring Technologies) in 2019. Unfortunately, we were not successful. After some discussions within the Executive Committee considering the needs of such a Training Centre, we decided to resubmit the proposal to make it stronger by addressing the reviewer comments and with the support of the original industry partners and some new industry partners. We proposed another training centre calling ATCSI (ARC Training Centre for Smart Data Driven Next Generation Infrastructure). Although we only had two months to resubmit the proposal, we considered that the proposal was stronger as it was prepared earnestly by Executive Committee. However, that funding application to establish this ATCSI was still not successful. We concluded that the scheme of Industrial Transformation Research Program (ITRP) to fund various training centres has been getting more and more competitive. The successful rate for the ITRP 2020 round for our application was only 16%. Also, looking at the comments we received for the proposed ATCSHM in 2019 and ATCSI in 2020, we got the same comment that “The proposed Project would have benefited from more clearly addressing one or more of the Industrial Transformation Priorities.” In the subsequent ANSHM EC meeting, we proposed 4 options in response to the outcomes of our two proposed ITTCs:

I. Make ITTC application more focused on civil infrastructure and re-submit, bearing in mind that civil infrastructure is still not one of the 6 identified priorities
II. Explore the opportunities of the two CRCs (Building 4.0 and SmartCrete) and try to see how ANSHM can work collaboratively within these two CRCs
III. Disperse the existing ITTC and submit as different ARC Linkage Projects (LPs)
IV. Not to submit any ITTC until ARC ITRP includes infrastructure

After much consideration, we would try to work on Options II and III and would also coordinate and encourage our members to participate any of the Industrial Transformation Research Hubs and Industrial Transformation Training Centre whenever there is a strong component in SHM research and development in these research hubs and training centres so that we could work collaboratively within ANSHM to promote SHM and work together. Our principle is to enhance collaboration without competition within ANSHM for the benefits of the country as well as for individual members. Hence, Prof Bijan Samali and I participated in establishing the ARC Industry Transformation Research Hub for Resilient and Intelligent Infrastructure Systems (RIIS) in Urban, Resources and

Energy Sectors, and recently, as mentioned in the last month updates, our participations into other research hubs or training centres are listed below:

1. Prof Bijan Samali as the 2nd named CI (Chief Investigator) of ARC Research Hub for Fire Resilience Infrastructure, Assets and Safety Advancements in Urban, Resources, Energy and Renewables Sectors
2. Prof Hong Guan as a CI of ARC Research Hub to Advance Timber for Australia's Future Built Environment
3. Prof Richard Yang as a CI of ARC Training Centre for Innovative Composites for the Future of Sustainable Mining Equipment

I strongly believe these two Research Hubs and the Training Centre can enhance us to work collaboratively within ANSHM to promote SHM.

Nevertheless, the more I participate in the RIIS Hub, the more I feel that if we ANSHM could have our own Research Hub or Training Centre, we could deliver more benefits to the engineering community as well as the public in the area of SHM. I notice that many of the Research Hubs or Training Centres in ARC are not easy to develop a team spirit that we ANSHM have as we have been working together for more than 12 years. I will give more discussions on this in the Research Collaboration section later in this update.

Option IV of our response states that "Not to submit any ITTC until ARC ITRP includes infrastructure". After waiting for two years, there are some priorities added to the ITRP Priorities, like Defence, Beverage, Critical Minerals Processing, Recycling and Clean Energy, and Space. However, Infrastructure has not been added as a priority. Does it mean that there could not be any proposed Research Hub or Training Centre on Infrastructure that could not be awarded? The answer is simply 'no". Just check the ITRHs or ITTCs established since the launching of the ITRP scheme, it can be seen that many of the Research Hubs or Training Centres are on Infrastructure, e.g.

- ARC Industry Transformation Research for Fire Resilience **Infrastructure**, Assets and Safety Advancements in Urban, Resources, Energy and Renewables Sectors (Awarded in ITRP 2022 round)
- ARC Industry Transformation Research Hub for Resilient and Intelligent **Infrastructure** Systems in Urban, Resources and Energy Sectors (Awarded in ITRP 2021 round)

- ARC Research Hub for Transforming Energy **Infrastructure** Through Digital Engineering (Awarded in ITRP 2020 round)
- 2017 ARC Training Centre for Advanced Technologies in Rail Track **Infrastructure** (Awarded in ITRP 2017 round.

Hence it is more important to write a proposal addressing one or more of the current nine priorities to support critical industries. Should we submit another proposal establishing a Research Hub or Training Centre, should we continue to work on what we have been working on instead of spending time and effort in preparing funding proposals to establish such Research Hub or Training Centre? These are all good questions for ANSHM community to consider. Any suggestion is welcome.

14th ANSHM Workshop - 24-25 November 2022, Sydney

Because of the availability of the University Technology of Sydney (UTS) Arial Function Centre, we need to swap the two-day event of the workshop as Day 1 to be a summit that explores various aspects of smart infrastructure and the 2nd day to be a technical workshop as follows:

Day 1: Smart Infrastructure Summit (by invitation) on 24 November 2022

The summit aims at providing a platform for three tiers of stakeholders to engage, inform and network, i.e.

- Tier 1: government agents, asset owners, construction industry;
- Tier 2: service providers and researchers, R/D institutes and
- Tier 3: equipment and IT suppliers.

This will allow sharing information, discussing challenges, sharing future visions, strategy and policy on implementation and application of digital transformation and intelligent infrastructure.

ANSHM Advisory Board Meeting (only for ANSHM Advisory Board and Executive Committee members) will be arranged after the presentations of Day 1.

Day 2: Technical Workshop (all are welcome) on 25 November 2022

The workshop will be about sharing the latest research/technology and applications of SHM and smart (intelligent) infrastructure in Australia and will be presented by leading Australian researchers and practitioners.

ANSHM Annual General Meeting (all are welcome) will be arranged during Day 2.

We are sincerely sorry for any confusion it may cause. We are updating the flyer because of this and will upload it to ANSHM Page in due course.

ANSHM 2nd Monograph
Please take note that the correct title for our (ANSHM) 2nd monograph celebrating ANSHM 10th Anniversary is "Recent Advances in Structural Health Monitoring Research in Australia" and not "Recent Advances in Structural Health Monitoring". It is my fault. Sorry for the confusion. Please click this link for the details of the book. I just like to repeat here that there are 11 chapters in the book arranged in five topic clusters: physical model-based updating and damage detection for bridges and buildings (Chapters 1, 2), smart and mobile sensor networks for bridges and partially submerged structures (Chapters 3, 4), data-driven machine learning based SHM method (Chapters 5 to 8), SHM in railway track maintenance and management (Chapters 9, 10), and finally, digital twin approach for lifecycle management of large-scale civil infrastructure (Chapter 11). It can be seen that SHM research is not limited and not just about installing sensors but to make sense the data collected as I shared at the beginning of this President Message. Anyone who would like to take advantage of the special publication discount of 20%, please enter code **special20** during checkout when you use the above link to purchase online. Multiple copy orders are welcome, and we offer bulk order discounts. To see the available discounts for multiple copy orders, please click here.

Research Collaboration
I am pleased to let you know that ARC has accepted the official start date of the ARC Industry Transformation Research Hub for Resilient and Intelligent Infrastructure Systems in Urban, Resources and Energy Sectors (ARC RIIS Hub) to be 20th July 2022. The 5 Themes of the Hub are listed as follows:

- Theme 1 Ubiquitous Sensing, Intelligent and Adaptive Systems
- Theme 2 Data collection, security and integration
- Theme 3 Modelling, Simulations and Prognostics
- Theme 4 Infrastructure Health Monitoring and Predictive Maintenance
- Theme 5 Spatial Data Infrastructures, Digital Twin and Decision Support

It can seen that it is very much like a research hub as a training centre for SHM. However, its direction, focus and application could be different from the normal applications for SHM. Actually, the training centres that we proposed in 2018 and 2019 are quite unique and the other established research hubs and training centres have not covered the areas that these proposed training centres aiming at. As mentioned earlier Prof Bijan Samali and I are the Theme Leaders of the Theme 4 Infrastructure Health Monitoring and Predictive Maintenance. Besides, Bijan and I are Business Development Director and Research Training Director, respectively. Although we are two leaders in the Hub, yet we still have difficulties in directing the Hub or even Theme 4 to be working towards the objectives of ANSHM because of different constraints. As stated at the start of this President Message, we should seriously consider the two questions that I mentioned earlier. I look forward to having that discussed in the next Advisory Board Meeting and the Annual General Meeting in the coming 14th ANSHM Workshop. Nevertheless, the RIIS Hub and other Research Hub, Training Centres, and CRCs could still provide many opportunities for us to have research collaborations amongst ANSHM members for the research and development in SHM, which has been well demonstrated for the achievements that we have made in these twelve years since its establishment in 2009.

Engineers Australia – Thought Leaders Series Webinar on SHM

As mentioned in the last monthly updates, I am invited to present an Engineering Australia webinar in November on SHM on 8 November 2022. I plan to speak for the first part and the second part to be conducted like the Industry Forum of ANSHM Workshops with some ANSHM members from the industry as a panel speaker in the forum discussion. The panel speakers include:

- Yew-Chin KOAY, Structural Engineering Advisor, Major Road Projects Victoria
- Govinda PANDEY, Chief Executive Officer of Rockfield Technologies Australia Pty Ltd
- Peter RUNCIE, Director of Natirar Consulting Services
- Isaac SCOT, Contracts and Structures Services Manager of Brisbane City Council

The confirmed date and time of the Webinar are as follows:
Date: 8 November 2022
Time: 1pm – 2.30pm (BNE)

More details including the registration will be provided in due course.

In the next sections, we will have two articles from our members. The first article is from Western Sydney University about utilizing nonlinear energy sink concept with a nonlinear damper to harvest energy for structural health monitoring and the other article is from the Deakin University on developing an acoustic-based pipe break early warning system in Adelaide City smart water network.

Stay safe and healthy!

With kind regards,

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Utilizing Nonlinear Energy Sink Concept with a Nonlinear Damper to Harvest Energy for Structural Health Monitoring

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Abstract

Supplying energy for structural health monitoring devices has always been a great challenge. Hence, harvesting energy from environmental sources has been attractive to researchers and engineers. For decades, the concept of nonlinear energy sinks (NES) has been investigated for passive vibration mitigation. An NES, which consists of a small mass attached to primary systems with a nonlinear spring and linear or nonlinear damper, presents a fast and irreversible capacity of efficiently dissipating energy from primary systems. Besides, this absorber is suitable for energy harvesting applications for generating electricity in vibrating mechanical structures. This work studies the performance of an NES that is connected to a linear oscillator with a combination of linear and nonlinear damping to enhance the output voltage of a piezoelectric element. The results of this work display that using a mixture of linear and nonlinear damping for NES can increase the output voltage from the piezoelectric element in a wide range of primary system frequencies.

Keywords: Nonlinear Energy sinks; Energy harvesting; Nonlinear Damper; Structural Health Monitoring; Piezoelectric

1. Introduction

Structural health monitoring (SHM) is the process of damage detection in various infrastructure including civil, aerospace and mechanical infrastructure. To attain this aim, technology is being developed to replace time-based maintenance procedures and qualitative visual inspection with more quantifiable and automated condition-based damage assessment processes [1]. In recent years, advances in sensors and information technologies have made SHM an effective data-driven method of ensuring the safety of civil infrastructure. In the last two decades, the issue of energy supply for health monitoring devices has become one of the critical topics investigated by researchers. Harvesting energy from sources that exist in abundance, such as vibration and thermal energy is an efficient solution [2].

Over the past few years, the use of piezoelectric components for harvesting mechanical vibration energy has attracted significant interests due to the incapability of electromechanical conversion. Numerous researchers studied power harvesting from vibration using piezoelectric materials and proposed their methodologies. Most SHM approaches use piezoelectric patches as sensors and actuators. There are two ways in which the piezoelectric effect works. When used as a sensor the patches utilize the direct effect where a charge is produced when the material is strained. Conversely, when a voltage is applied to the material, it will deform proportionally to the applied potential difference. This allows such materials to be used as actuators [3]. Multiple arrays of these devices can be configured to produce sequential local motions on a structure, and the response to these motions can also be measured using the same array [4].

By applying mechanical strain to piezoelectric materials, power can be harvested from vibrations. Because of their high impedance, these devices produce large voltages and small currents. For instance, a cantilever beam equipped with piezoelectric sensor and a proof mass generated 4mW for 1.53g at a resonant frequency of 5Hz for railway applications [5]. Microelectromechanical systems (MEMS) consisting of several piezoelectric cantilevers have been shown to generate 11nW at a resonant frequency of 35.8Hz and an acceleration level of 0.1g[6]. The above-mentioned research has relied on resonant devices, however in most cases the harvesters are subjected to broadband vibrations. One way of producing broadband energy harvesters is to introduce non-linearities into the system[7]. Experimental studies of piezoceramic actuators for power generation found that MIDE Quickpak devices without interdigitated electrodes showed the greatest power output [8]. Vibrations are one of the vast energies in nature and exist in many mechanisms that are not very pleasant for structures, and one of the concerns of humanity throughout history has been to prevent unwanted vibrations in structures. This goal has caused the construction of passive and active absorbers to prevent vibrations in the systems. Usually, passive absorbers try to reduce the vibrations of the systems by absorbing the vibrations of the primary systems. One of the pure ideas for harvesting energy is to use these vibration absorbers so that both the vibration of the system can be prevented, and these vibrations generated in the absorber can be used to generate electricity.

One of the best types of energy absorbers is nonlinear energy sinks (NES). This controller absorbs the energy of the primary system by matching itself to the frequency of the primary system. The most common type of NES consists of a mass, cubic nonlinear spring, and linear/nonlinear damper that is coupled to the primary system with a proper design. Energy absorbed by the NES can be harvested using an electromechanical device. In order to convert sufficient amount of energy, the corresponding deformation of the piezoelectric material should be large enough. Nowadays, considerable research has been carried out on NES for energy harvesting. For instance, Gabriel P. Araujo et al. [9] examined the combination of a rotational NES with EH for the vortex-induced vibrations of a cylinder exposed to airflow. Youzuo Jin et al. [10] proposed an apparatus for simultaneous vibration suppression and energy harvesting via NES in a broad frequency band. Haiqin Li et al. [11] offered a new energy harvester using vibro-impact nonlinear energy sink. Nili Ahmadabadi et al. [12] presented an optimal design for a system comprising a nonlinear energy sink and a piezoelectric-based vibration energy harvester. The energy harvester is used for scavenging vibration energy dissipated by the NES. Danilo Karličić et al. [13] examined the dynamic model of an axially moving beam with a nonlinear energy sink and a piezoelectric device.

While a lot of research has been performed to develop NES for use in various applications, no study has been carried out to investigate the performance of this type of absorber with nonlinear damping for energy harvesting. This article has investigated the performance of NES with non-linear stiffness and damping and their combinations to develop the harvested energy for different systems such as structural health monitoring systems and its comparison with the linear damping state of NES.

2. Definition of the system

Figure 1 depicts a linear oscillator (LO) coupled to an essentially nonlinear energy sink and a piezoelectric element in order to harvest energy from the NES.

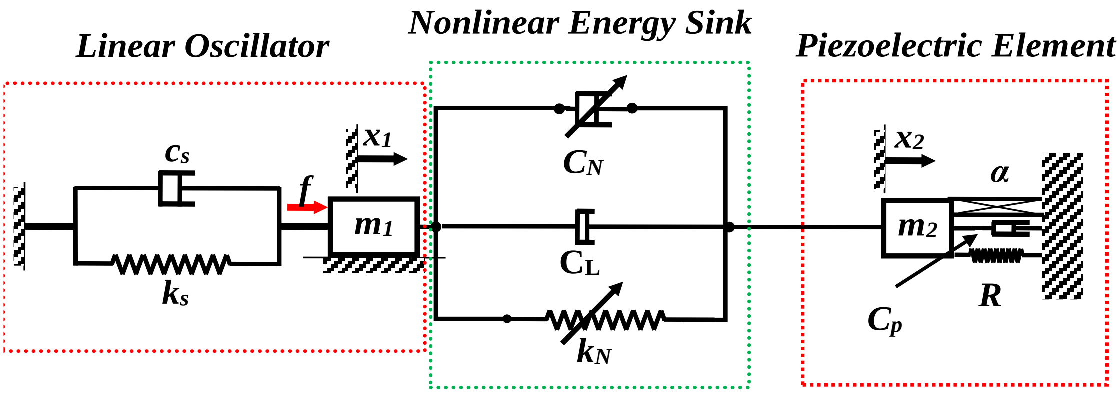

Figure 1. Schematic view of a linear oscillator, nonlinear energy sink and piezoelectric element.

In this structure, M, k_s and c_s are, respectively, the mass, stiffness and damping of the primary system and k_N, C_L, and C_N are, respectively, stiffness, linear damping and nonlinear damping of the attachment. In this configuration, the piezoelectric element is located between the NES mass and the ground. Where k_p is the equivalent stiffness of the piezoelectric layer when it is short-circuited, α is the force factor, C_p is the clamped capacitance of the piezoelectric element, and F_p represents the driving force. If *I* is defined as the outgoing current, and *V* as the voltage of the piezoelectric elements, the piezoelectric equations can be expressed as:

$$F_p = k_p x + \alpha V \tag{1a}$$

$$I_p = \alpha x - C_p V \tag{1b}$$

According the ref. [12], the governing equation of the model is given by:

$$R\dot{I}(t) + \frac{1}{C_p} I(t) - \frac{\alpha}{C_p} x_2 = 0 \quad (2)$$

By defining the variables x_1 for the displacement of the initial system, and x_2 as the nonlinear adsorption displacement, the governing equations of motion of the LO with a nonlinear attachment are obtained using Newton's law as follows:

$$M\ddot{x}_1 - k_s x_1 + c_s \dot{x}_1 + \varepsilon k_N (x_1 - x_2)^3 + \varepsilon C_L (x_1 - x_2) + \varepsilon C_N (x_1 - x_2)^3 = f cos(\omega t) \quad (3a)$$

$$\varepsilon \ddot{x}_2 + \varepsilon k_N (x_2 - x_1)^3 + \varepsilon C_L (x_2 - x_1) + \varepsilon C_N (x_2 - x_1)^3 + \varepsilon k_p x_2 - \frac{\alpha}{C_p} I(t) = 0 \quad (3b)$$

$$R\dot{I}(t) + \frac{1}{C_p} I(t) - \frac{\alpha}{C_p} x_2 = 0 \quad (3c)$$

Where the dot denotes the differentiation with respect to time (t). ε and the f are defined as the ratio of absorber mass to the primary system and harmonic excitation form, respectively. Given this issue that the smallest changes in the variables of the system lead to considerable results, all of the variable parameters are multiplied by ε.

3. Results and Discussion

The main purpose of this section is to investigate the effects of the nonlinear damping of the NES on the dynamic behavior of the system. To this end, the nonlinear dynamical behavior of the coupled system will be revealed via numerical integrations of the equations of motion of the system. To study the above system, the values listed in Table 1 for the parameters of the dimensionless system have been used.

Table 1. The values of the parameters used in the analysis.

Parameters	M	k_s	c_s	C_p	k_N	f	ω	ε	α	k_p	R
Values	1	1	0.01	1	0.6	1	1	0.01	0.027	0.1	1.1

Since the amplitude of the system vibrations has a direct relationship with the output voltage value, in this section, the time history graphs of the absorber connected to the system have been examined.

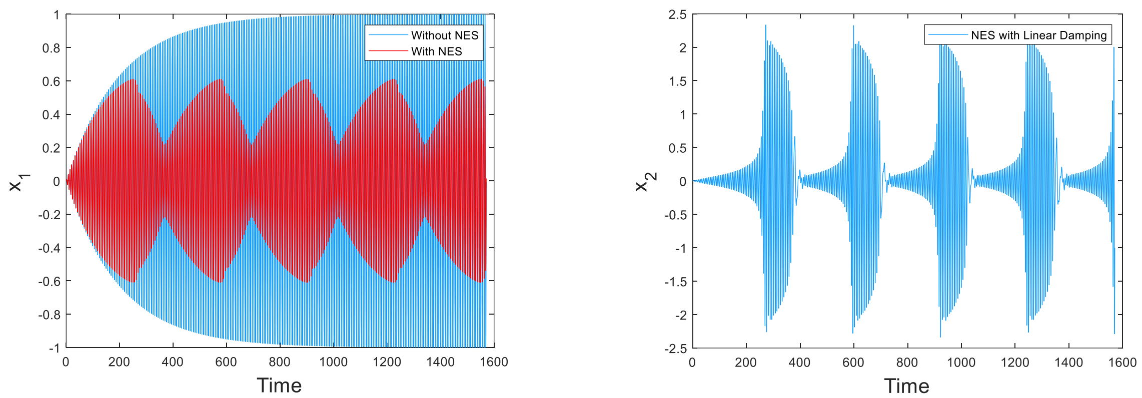

Figure 2. The time history diagrams for primary system attached to a LDNES.

To investigate the effect of the NES with linear damping (LDNES) on the behavior of the system, the time response diagram of the primary system in two states without the presence of NES and with its presence is shown in Fig. 2. As shown in the figure, with the connection of the absorber, the behavior of the primary system has completely changed and caused vibration with the desired frequency in the LDNES. According to the amplitude and frequency of the primary system and the absorber in Fig. 2, it is quite clear that the harvesting of energy from the absorber is much more favorable than the harvesting of energy from the primary system. In the following, the behavior of the NES with nonlinear damping (NDNES) has been investigated by converting the absorber damping to a non-linear form. As can be seen in Fig. 3, in the absorber mode with nonlinear damping, although it has caused a decrease in the maximum value of the amplitude, it has increased the number of frequency peaks. For better clarity, the wavelet graphs of the absorber signal are illustrated for two modes of linear damping and non-linear damping in Fig. 4.

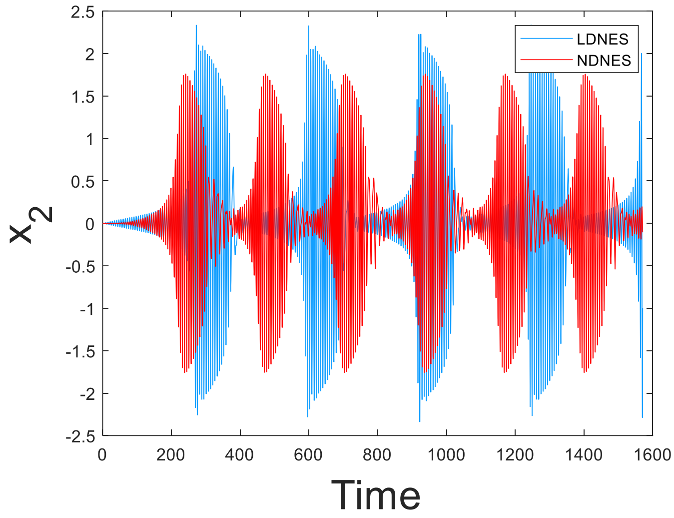

Figure 3. The time history diagrams for comparing the performance of LDNES and NDNES.

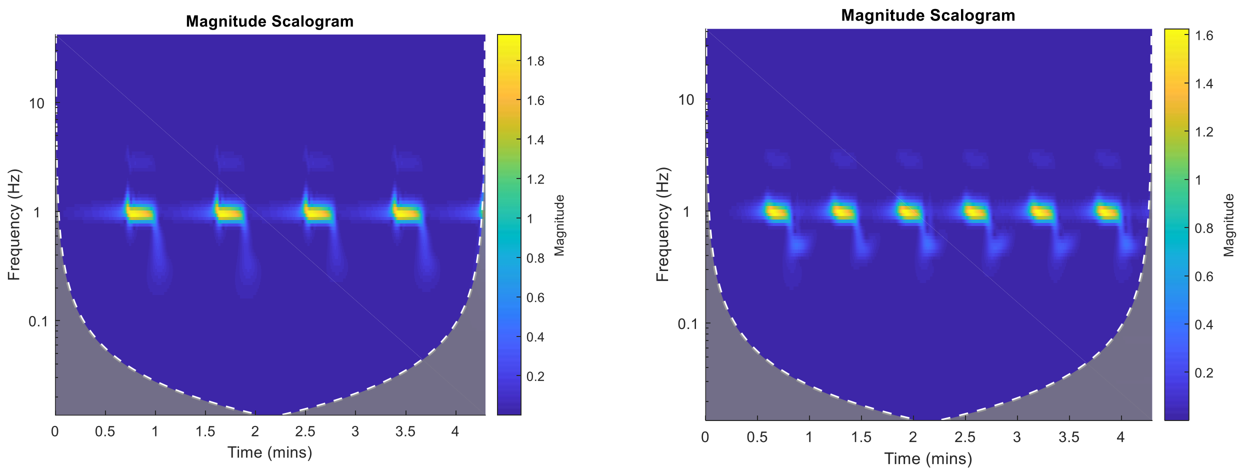

Figure 4. The wavelet diagrams for LDNES (left), and NDNES (right).

As we know, the vibrations of the system can be applied to the primary system at different frequencies, so the effect of nonlinear damping on the amplitude of the absorber is investigated and its performance is compared with the absorber with linear damping. Thus, the following equation is considered to exanimate the response of the system around its fundamental natural frequency.

$$k_s = \omega^2 + \varepsilon\sigma \tag{4}$$

Where σ is the detuning parameter. One of the essential tools for examining the voltage signals is the concept of root mean square (RMS). Fig. 5 shows the RMS for several configurations of LDNES and NDNES. As can be seen, as the LO approaches the natural frequency, a greater amount of the voltage is obtained with the existence of nonlinear damping in the NES. However, for the far σ from the natural frequency, the NDNES is not the best attachment to harvest energy for generating electricity. Therefore, a combination of linear and nonlinear damping could be made a high level of voltage in all ranges of σ. This diagram displays that with $c_L = 0.2$ and $c_N = 0.2$, the system can present a high level of voltage.

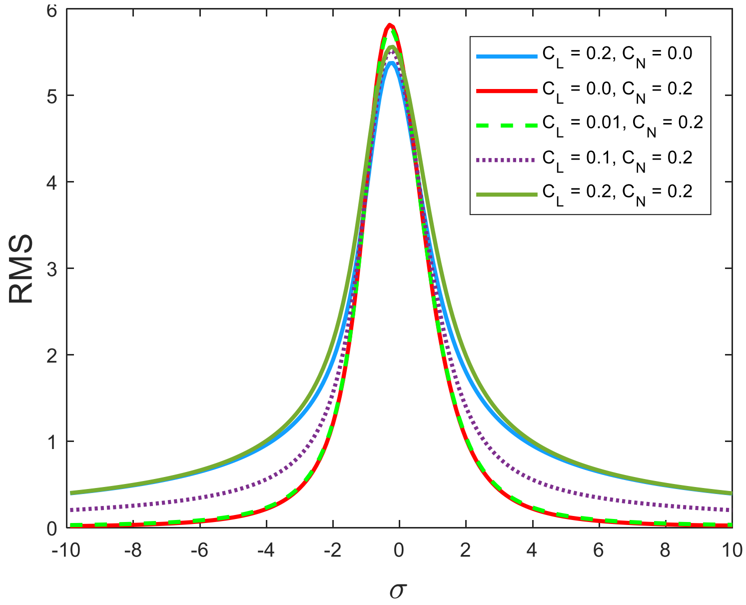

Figure 5. RMS diagram for various values of c_L and c_N.

4. Conclusion

The issue of energy supply for instruments used for structural health monitoring has become one of the major issues. Harvesting energy from sources that exist in abundance, has been identified as an effective solution.

Since the absorbers are devices that have recently received attention due to their high energy level in order to harvest energy for mechanical systems, the performance of an NES as one of the best types of vibration absorbers was investigated in the present work. In this article, to increase the performance of NES connected to a piezoelectric element in energy harvesting, a combination of linear and non-linear damping was used. The simulation results showed that absorbers with non-linear damping in a range of frequencies have better performance in generating electricity by piezoelectric element compared to linear damping. Also, the results indicated that by using an optimal combination of linear and non-linear damping, the performance of the piezoelectric element can be improved to increase the output voltage.

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Acoustic-based pipe break early warning system in Adelaide City Smart Water Network

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Abstract – Recent advancements in structural health monitoring technologies have enabled the development of smart water networks (SWNs). The monitoring is typically through distributed Internet-of-Things (IoT) sensors, and the information enables proactive asset management of large water networks. This article presents an overview of the recently developed acoustic-based pipe break early warning system in Adelaide City SWN. The system includes hundreds of IoT-based accelerometers, a cloud-based data visualisation platform and customised data analytics for near real-time detection of new and/or developing leaks. The early detection enables proactive maintenance, which then prevents uncontrolled pipe breaks that would result in significant water service interruptions, property damages and traffic delays. The system has been used by the operators in South Australian Water Corporation since 2019 and has contributed to about 50% reduction in uncontrolled pipe breaks in Adelaide City.

Keywords – leak-before-break, pipelines, smart water networks

1. Introduction

Structural health monitoring (SHM) and condition assessment of water distribution systems (WDSs) are critical to ensure water security. Australia has an estimated 200,000 km of water mains (about five times the length of equator), and experiences about 36,000 water main breaks every year (about 18 per 100 km of pipe) (Bureau of Meteorology, 2022). The leaks and breaks in our WDSs result in an annual water loss of about 255 giga litres (GL) (Bureau of Meteorology, 2022), equivalent to the annual water consumption of 1.5 million homes (~3.7 million people).

The conduction of SHM and condition assessment of buried water pipelines is difficult and costly. Most pipe wall condition assessment techniques are localised [e.g. ultrasonic, or magnetic flux leakage based wall thick ness detection (Liu and Kleiner, 2013)] or only cost-effective to short distances (e.g. CCTV). Pipe condition assessment techniques based on transient pressure waves can cover up to kilometres in one test, but the spatial resolution is low (about 10 to 20 m) (Gong et al., 2015). For leak management in WDSs, passive acoustic listening and correlation is the most common practice (Gupta and Kulat, 2018). However, conventional acoustic-based leak detection typically is only applied to selected pipes where the existence of leaks is known or suspected, since the practice is labour intensive and rely heavily on the experience of the operators.

Recent development of wireless acoustic and pressure sensors has enabled continuous monitoring of large water networks (Obeid et al., 2016). Early detection of pipe bursts (after their occurrence) using permanent pressure sensors has been a research focus (Stoianov et al., 2007; Zan et al., 2014; Zecchin et al., 2022), and such systems have been implemented in several WDSs, including the Adelaide City water network (Stephens et al., 2017). It is very difficult for pressure sensing systems to detect small leaks (new or existing). For the detection of small leaks in WDSs using permeant acoustic sensors, the progress and application are limited, and the focus has been largely on non-revenue water reduction (Farah et al., 2017).

South Australian Water Corporation (SA Water) has been developing smart water networks since 2017 (Stephens et al., 2020a). Among several different types of sensing systems been implemented, a permanent acoustic monitoring sensing network has been established in the Adelaide City water network for early warning of pipe breaks (Stephens et al., 2020b). The early warning is based on near real-time detection of new or developing pipe leaks (through-wall cracks), which overtime may result in unstable crack growth and pipe breaks (Rathnayaka et al., 2017). This application is new and different from the traditional leak detection for water loss reduction that has a low requirement on timeliness and reliability. The pipe break early warning system is under business-as-usual (BAU) operation in SA Water, and has contributed to about 50% reduction in uncontrolled pipe breaks in Adelaide City (Stephens et al., 2019).

This article provides an overview of the acoustic-based pipe break early warning system in Adelaide City smart water network. The accelerometer sensing network and the cloud-based visualisation platform are briefly described. The development of the customised data analytics is then presented. Practical challenges experienced in the field are also discussed. The conclusion highlights key considerations for establishing SWNs.

2. Accelerometer Sensing Network

305 accelerometers (Ortomat-MTC, von Roll, Switzerland) were commissioned across the Adelaide City water network in the first phase of the rollout in 2017. Overtime, the number of sensors has increased to about 500 and the coverage has extended to North Adelaide. The accelerometers are connected magnetically to existing pipe fittings, such as valves and hydrants, in underground chambers (Figure 1).

Figure 1. Photograph of valve chamber with installed VonRoll accelerometer, logger and antenna [adapted from Stephens et al. (2018)]

For most time of the day, the measured vibration signals are pre-processed in the data logger to produce a single-value noise level every 10 minutes (configurable). Around 2am in the early morning (configurable), a 10-second vibration signal is recorded and stored as a .WAV file. The recorded data (noise levels and the .WAV file) are transmitted to a cloud-based data management system once a day at a predetermined time through the 3G or 4G mobile network. The data transmission can also be triggered by locally configured thresholds for alarms.

3. Cloud-based Visualisation Platform

A could-based data management platform (VIEW, Visenti, Singapore) is used to visualise the data. This platform caters for multiple types of data from various sensors in the smart water network (e.g. acoustic, transient pressure, low-rate flow and pressure, water quality). A separate dashboard platform has been developed in the Microsoft Azure environment (Figure 2). This platform enables easy integration of customised data analytics.

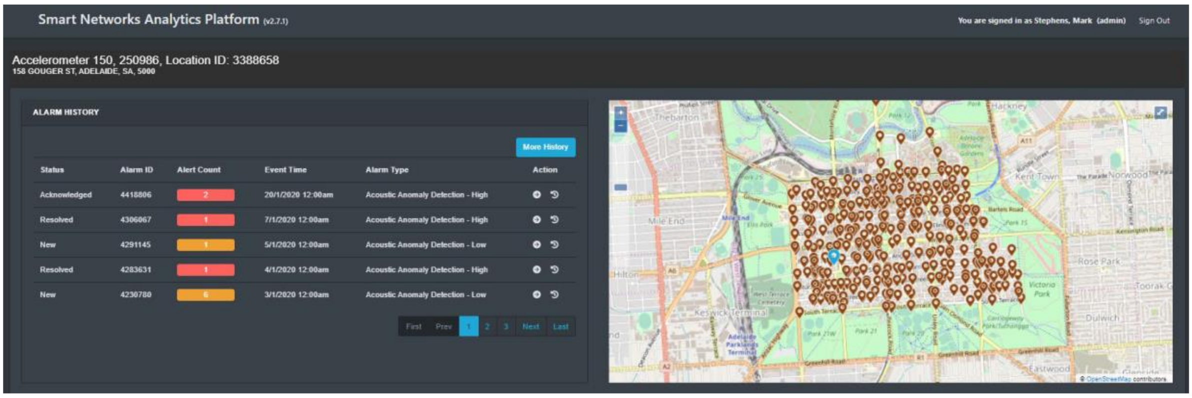

Figure 2. A screen shot of the data management and visualisation platform developed in the Microsoft Azure [adapted from Stephens et al. (2020c)].

4. Customised Data Analytics

Multiple data analytic techniques have been developed to analyse the acoustic noise level data and the .WAV signals. The algorithms are based on statistical analysis, spectral analysis, and machine learning. The results from multiple techniques are cross referenced to enhance the rate in successful detection and reduce the rate of false alarms. Since the application of pipe break early warning was new, the data analytics were developed "from scratch".

Some statistical-based algorithms have been developed to detect changes in the acoustic noise level time series (Zhang et al., 2020). Key statistical methods involved include median and interquartile range analysis, cumulative sum method (CUSUM) and Kalman filter. Figure 3 shows some of the results in the dashboard developed using Microsoft Azure. These algorithms can be applied to the high-resolution acoustic noise level data (e.g. every 10 minutes) to detect fast changes, or can be applied to the daily minimum noise level data to detect changes in trends over a time window of several days.

Figure 3. A screen shot of the acoustic data analysis results [adapted from Stephens et al. (2020c)].

Several techniques have been developed to analyse the .WAV data, which provides much more information and enables more advanced analysis. Each data file provides the vibration information at a sampling frequency of 4681 Hz and for a duration of 9.995 seconds. Typically, only a single .WAV file as such is recorded at each sensor for each day.

One technique uses the median frequency (MF) and the root-mean-square (RMS) values together for detecting new and/or developing leaks (Gong et al., 2020). Each .WAV data is divided into a number of short-duration data frames through windowing. This enables more robust determination of the MF and RMS, especially for data files with transient interference (e.g., noise from a passing vehicle). Each .WAV data file will produce one representative MF value and one representative RMS value. They are the L90 values determined from the MF and RMS values of all the data frames, e.g., L90 MF is the representative value and 90% of the MF values are higher than that. The MF and RMS values across multiple days are then analysed together using statistical analysis for change detection. Figure 4 provides an example of the analysis.

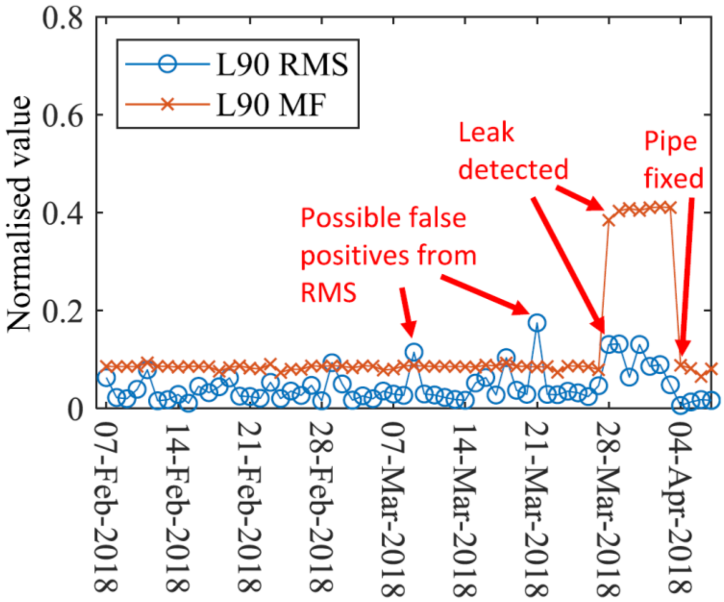

Figure 4. L90 RMS and L90 MF values calculated for an acoustic logger [adapted from Gong et al. (2020)].

Field investigations indicate that some of the through-wall pipe cracks can grow steadily over weeks to months. Continuous monitoring and assessment can help with dynamic adjustment of priority and work order scheduling (i.e. not all leaks and cracks need to be dealt with immediately). A technique is developed to assess the rate of change in the .WAV noise power levels over weekly or monthly periods (Stephens et al., 2022). It also helps to detect slow growing crack at early stages.

Machine learning techniques have been developed based on support vector machine (SVM) and convolution neural networks (CNN). The large amount of data from hundreds of sensors, together with field investigations on the nature of the leaks, enable effective training to machine learning models.

To develop the SVM model (Zhang et al., 2022a), 12 acoustic features (such as zero cross rate, spectral centroid and spectral spread etc.) were extracted from the selected .WAV files labelled as "crack/leak" or "no crack/leak". They were then used to train a SVM model. The accuracy of the final SVM model is 96.9% for the test data. Over an eight-month period from January 2020 to August 2020, six pipe cracks were detected (Figure 5 shows a circular crack). In addition, 23 valve leaks, 10 water meter leaks, and 25 connection and consumption leaks (including leaks on the customer side) were also detected.

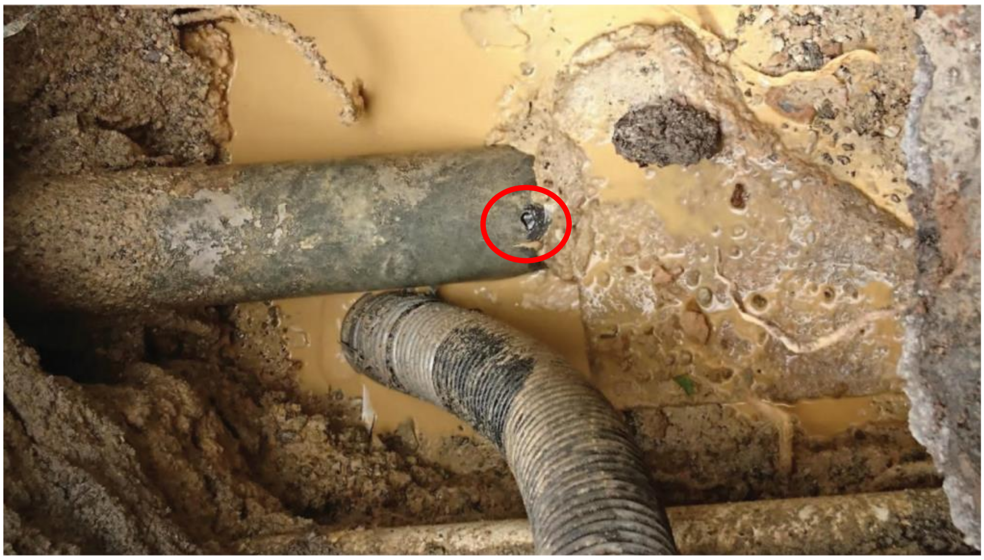

Figure 5. A circular crack (thumb sized hole, highlighted in the red circle) detected on a 150 mm mild steel cement lined (MSCL) pipe [adapted from Zhang et al. (2022a)].

Along with the development of the SVM model, a CNN model is developed to classify newly measured .WAV data into four categories: “anomaly”, “background”, “intermittent environmental noise” and “persistent environmental noise” (Zhang et al., 2022b). For those “anomalies”, a Siamese CNN model is used to further determine whether it is related to a regular/irregular scheduled event (e.g., customer water use) or a new anomaly. An advantage of the CNN model is that it does not require prior selection of features from the .WAV files. The accuracy of the CNN technique is 92.4% for the validation data.

5. Challenges

There are many challenges associated with large scale implementation of SWNs. Some of the key aspects are summarised as follows:

Logistics in the field

The large number of sensors are expensive new assets for water utilities to maintain. Issues such as flat batteries, loss of communications, sensor malfunctions, etc. occur on almost a daily basis for large-scale sensing networks. A dedicated team is needed to maintain the sensors in the field and ensure the continuous supply of quality data.

A dedicated team is also needed to conduct timely field investigations. A key purpose of SWNs is to shift the asset management from reactive to proactive. This requires a change in mindset of the maintenance crew. In the long term, proactive maintenance saves money and resources when compared to the reactive practice.

False alarms

For business-as-usual (BAU) operations, the rate of false alarms must be very low to make the operation sustainable. False alarms waste resources, and more critically, it reduces confidence in the project and the team. However, it should be noted that false alarms are almost inevitable, and they also help with the development of the smart water systems.

It is important to investigate and understand the causes of the false alarms. Sometimes it is because that the technology is not designed for the specific application or hasn't been customised to the specific water system. Further research and development may be needed to reduce the rate of false alarm, especially for the data analytics, as discussed more in the next subsection.

Data analytics

Most applications of SWNs are different from traditional practices thanks to the new capabilities provided by smart water technologies. Different from the sensing networks and data management platforms that are relatively easy to be standardised, the data analytics typically need to be developed or adjusted for specific applications and for specific water systems. As in the case reviewed in this article, using the same IoT-based accelerometers, the requirements on data analytics for pipe break early warning are different from that for non-revenue water reduction.

Lack of or low performance of data analytics is one of the key reasons that preventing many smart water initiatives to extend from field trials to rollouts. Technology end users typically do not have the technical capability to develop advanced data analytics. The off-the-shelf solutions typically are not customised for the specific water system or the specific application, which can result in high false alarm rates.

Collaboration among technology end users (e.g. water utilities), commercial technology providers and researchers is necessary for developing effective data analytics for new applications/systems. The success of the Adelaide SWN is built on broad partnerships and more information can be found in Stephens et al. (2020a).

6. Conclusion

This article summarised the key aspects of the acoustic-based pipe break early warning system in Adelaide City smart water network. Key findings from this project include:

- Recent development in IoT sensing technologies has enabled large scale application of smart sensing networks in water distribution systems.
- Commercial products are available for effective data management and visualisation. The platform can handle multiple types of data from various sensors.
- Implementation of SWNs demands transformation of the way of operation. System operations and asset maintenance need to be more proactive based on the new information collected. It is much more than a capital delivery project.
- Research and development may be needed to make sure the data analytics is effective for the specific application or water system. This typically requires upskilling of the staff and partnerships with research providers.

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