Proceedings IRG Annual Meeting (ISSN 2000-8953)

IRG/WP 23-50380

THE INTERNATIONAL RESEARCH GROUP ON WOOD PROTECTION

Section 5 **Sustainability and Environment**

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Paper prepared for the IRG54 Scientific Conference on Wood Protection
Cairns, Australia
28 May – 1 June, 2023

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ABSTRACT

Timber structures decay over time with degradation in their structural integrity. Changing environmental conditions, varying loads, exposure to moisture or insect attacks lead to changes in their vibrational response behaviour. Here we present a low-cost device used as a triggered exciter to enable the monitoring of the structural integrity of timber bearers or even power poles in electricity networks. The actuation is initiated by a novel purpose-built, calibrated spring-loaded piezo-electric exciter. The device is connected to a fibre-optical network with optical accelerometers to transmit signals over large distances for processing purposes with the potential to be connected to a sensing network. Preliminary results of the actuators are presented to highlight the robustness of the signals and the controllability of the force using simple screw fixations. Implications of these results and further work to enable practical structural health monitoring of timber poles will be discussed.

Keywords: Timber health monitoring, micro-actuator device, vibration assessment.

1. INTRODUCTION

Timber structures and frames can be assessed for damages due to decay, insects, delamination and cracks, large deformation, and moisture (Palma and Steiger 2020). There are several methods for detection of damage in timber-made structures including acoustics and vibration-based techniques. In the case of vibration, a damaged timber element has a different response to an excitation compared to its undamaged state (Palma and Steiger 2020). Hence, by measuring the vibration response of timber structure before and after the occurrence of damage, we can detect the damage incident and in principle its growth over time. Shaker excitation or impact hammer testing can be used for vibration-based health monitoring of timber structures. However, the use of these technologies represents relatively more expensive options for the continuous monitoring of the structures. An alternative can be a custom-built actuator that is much cheaper and can be mounted on the structure for continuous excitation.

A micro-mechatronic system can be used for continuous monitoring of timber structures. Generally, it should possess a micro-processing unit or micro-controller, a sensing/actuation unit and an interface between the electronic and mechanical parts (Ishihara *et al.* 1996). There are different actuation methods for such systems, including electromagnetic, electrostatic, optical, and piezoelectric actuation. For health monitoring of timber construction and support elements, actuation with piezoelectric patches that are off-the-shelf products can be a commercially viable solution. One major advantage of piezoelectric actuation is due to the relatively fast response of the piezoelectric ceramic to an input voltage, with relatively precise travel range (Higuchi *et al.* 1990). There are piezoelectric actuators that are built from a stack of piezo-ceramics and calibrated for high precision of up to nanometers displacement (Tofigh *et al.* 2021). However, for structural health monitoring, a single layer piezo-patch will suffice if it is characterised fully. This leads to a significant cost reduction, encouraging a network of such actuators for monitoring timber structures.

For large timber structures such as power poles, a network of sensors might be needed to monitor the health and detect damages. Connecting the sensors with conventional electrical cables requires a network in which all sensors are directly connected to a central Data Acquisition system (DAQ). An alternative is to use a fibre-optic network using advanced electrical to optical transduction (Brodzeli *et al*. 2013) and a well-known wavelength division multiplexing technique (Krauss), allowing daisy-chaining multiple sensors on one fibre-optic cable connected to a to the DAQ. This optical network can be the future of network-sensing, avoiding signal attenuation at large distances, when connected and characterised well with conventional sensors such as accelerometers.

In this paper, we present a bespoke micro-actuation mechanism that allows the continuous actuation using a cheap piezo-ceramic for samples of construction timber elements. This micro-actuation mechanism consists of a purpose-built micro-actuator (MiAC) as a derivative, in-house design of (Oberst *et al.* 2022), in combination with piezo-elements (Tofigh *et al.* 2022), which is characterised and validated using an accelerometer that is conventionally and optically connected to the DAQ (a bespoke optical accelerometer based on liquid crystal technology (Brodzeli *et al.* 2022). A test protocol on a test structure is developed here to be used for the implementation of a series of micro-actuator and micro-sensors on timber structures for vibration-based health monitoring and detection of miniscule vibrations (micro-vibrations in the following) with a lower cost and enhanced Signal-to-Noise ratio, e.g. for damage detection in a noisy environment.

2. EXPERIMENTAL METHODS

The experimental measurements were conducted using a plank of Pinus radiata with dimensions 1,200 mm × 90 mm × 8 mm (approximate weight 475 g). It is untreated and cut along the grains with no visible knots. At the support, about 200 mm length of the plank is sandwiched between a block of steel and a thick block of timber to distribute the pressure across the width of the plank. The free span of this cantilever beam is 1000 mm, and the impact point from the micro-actuator and an automated impact hammer with stainless steel tip (NV-Tech Scalable Modal Hammer SAM1) is at l = 200 mm from the support. The entire setup is placed on an optical table (anti-vibration, Kinetic System, VIBRAPLANE 500P-28-4) to minimise the vibration noise (noise level of below 1 μm/s2). The impact hammer with a nominal linear force range of 2 mN to 200 N was used to generate consistent single-hit impulses at the excitation point in the middle of the plank cross section at l = 200 mm. Later, our proposed micro-actuator device was placed at the same location to generate the impulse force. Different lengths of the screw attached to the piezo-transducer were used to investigate the response level to the same excitation signal. An M4 stainless steel wood screw, penetrating the plank by two threads about 4 mm, is being used to implement a controllable stiffness and force transduction mechanism; hence, the influence of its length on the excitation level and consequently on the response is to be investigated. For test repeats, the wood screws that were initially connected by a screwdriver were removed and placed back on the same hole.

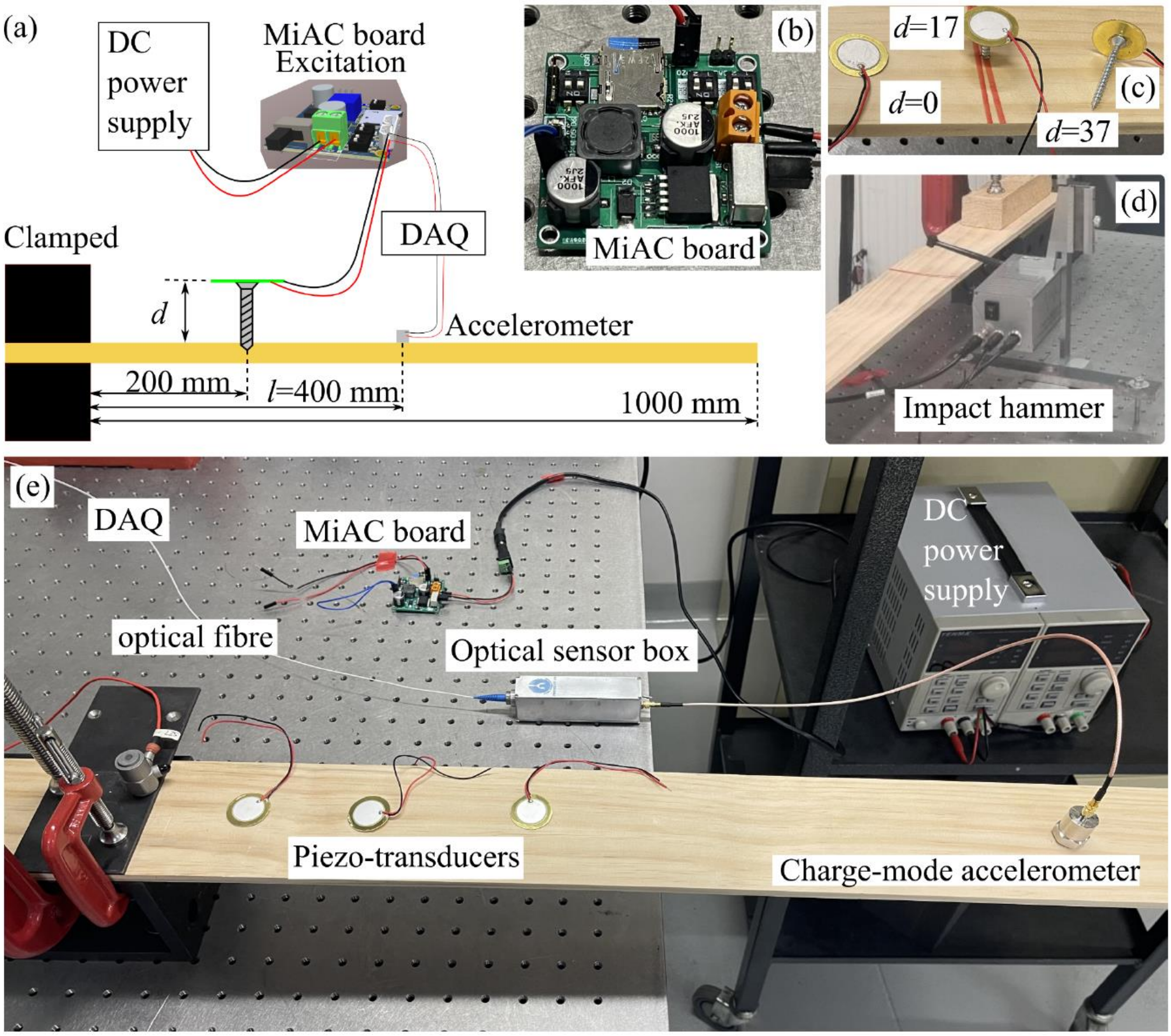

Figure 1: Experimental setup for testing the vibration sensing in timber plank of 1,000 mm × 90 mm × 8 mm made of untreated pine, cut along its grain: (a) schematic with bespoke Micro-Actuator (MiAC) board generating the excitation signal, and connected to Data Acquisition system (DAQ), and (b) close-up view of the custom-build MiAC board, (c) piezo-transducers mounted on screws of different lengths for generating the impulse excitation, and (d) the automated impact hammer for generating the impulse excitation. The plank is clamped at one end on an anti-vibration table and the accelerometer is placed at l = 400 mm and 600 mm, to test for various signal strength using an automated impact hammer; (e) close-up view of the components in the setup including the PhoenixZ optical sensor box as a part of the optical accelerometer

The piezo-transducer (ceramic transducer AB3342, validated in Tofigh *et al*. 2022) shown in Fig. 1 as a green-solid layer on the screw is connected to our custom-built electronic board that can produce impulse excitation signals or other special signals at user-defined intervals. For these tests, we generate an impulse signal every second and use the same intervals for impact hammer testing. The excitation signal is sent to the DAQ (National Instrument cDAQ-9171) along with the acceleration signal from a reference accelerometer (Sinocera Piezotronics Inc. CA-YD-127 with

1615.08 mV/m/s^2 sensitivity factor including Dytran inline charge amplifier). For the testing of the optical network, we use the same charge-mode accelerometer that can integrate well with the optical transducers and multiplexer. A schematic of the optical accelerometer is shown in Fig. 2.

3. RESULTS

Experimental tests were conducted using the setup, shown in Fig. 1, to investigate the performance of the MiAC device at different input voltages and three lengths of the connecting screw. We also investigate the measured data of the optical accelerometer for the impulse excitation by comparing against the reference accelerometer.

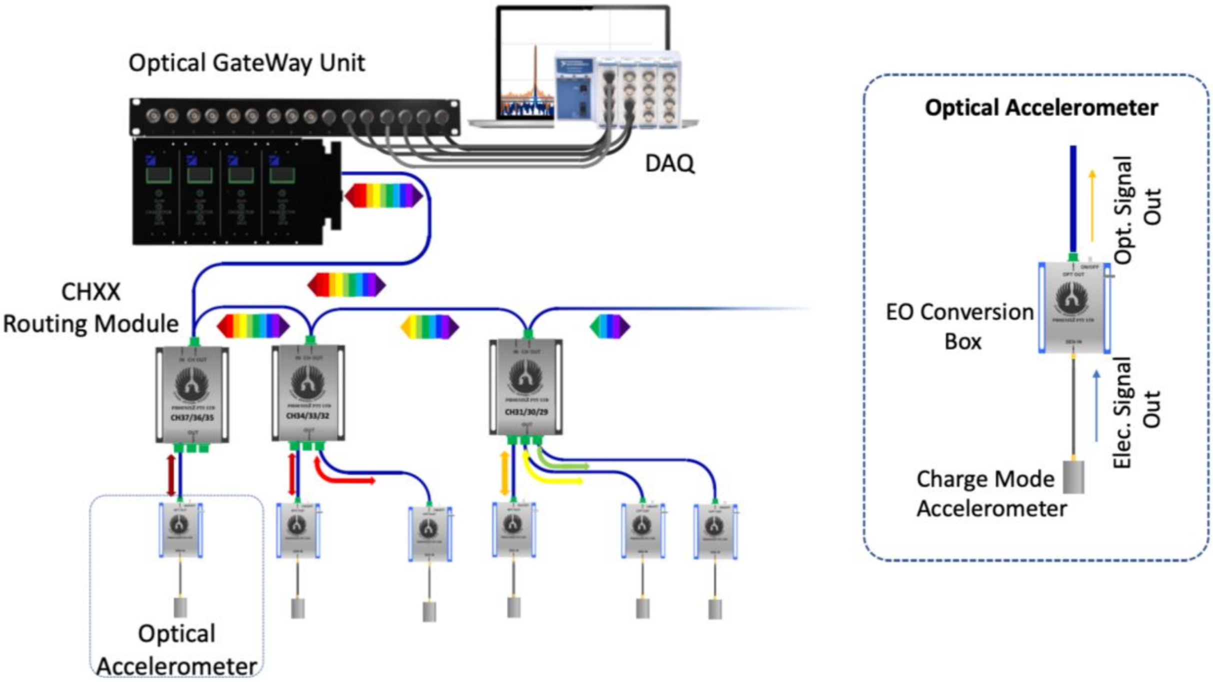

Figure 2: A schematic diagram of the concept of the optical network for measuring acceleration using a charge-mode accelerometer. The optical accelerometer is comprised of the charge mode accelerometer connected to an electrical-to-optical (EO) conversion box using short (up to 300 mm), shielded electrical cable enabling low-noise transmission of low electrical power (up to 0.0018 microwatt) generated by the charge mode accelerometer. The EO conversion box linearly (THD -40 dB) converts those electrical signals to optical. (Brodzeli *et al.* 2013)

The system works through measuring the light reflected by the optical accelerometer. Light is delivered to the optical accelerometer by a single mode optical fibre (SMF-28). Dense Wavelength Division Multiplexing (DWDM) is used to multiplex multiple sensors on one optical fibre. In this technology broadband light from a suitable source is transmitted from the optical GateWay Unit down the optical fibre. When the light encounters a routing module CHXX , a small wavelength range (analogous to a 'colour' of light), is dropped off and directed to the sensor, while the remaining light continues downstream until the next router is reached. Here, another 'colour' is dropped off to an attached sensor. In this manner, multiple sensors can be addressed using broadband light divided into channels. Upon reflection by the sensors, each channel is recombined back into the fibre and transmitted back towards the source to the optical GateWay Unit where it is split into different colours/channels again and directed to the photodetectors to be transformed into electrical domain for further analyses. In Fig. 3, the acceleration magnitude of the optical accelerometer is shown before and after calibration for frequency range 100 Hz to 2,000 Hz. The results are compared with the reference accelerometer to demonstrate the applicability of the optical accelerometer. The excitation was generated via mechanical impulse from the automated impact hammer showing a peak force of 1.5 N ± 0.2 N at 51,000 Hz sampling rate. The accelerometers were placed at l = 400 mm that is 200 mm distance from the point of impact.

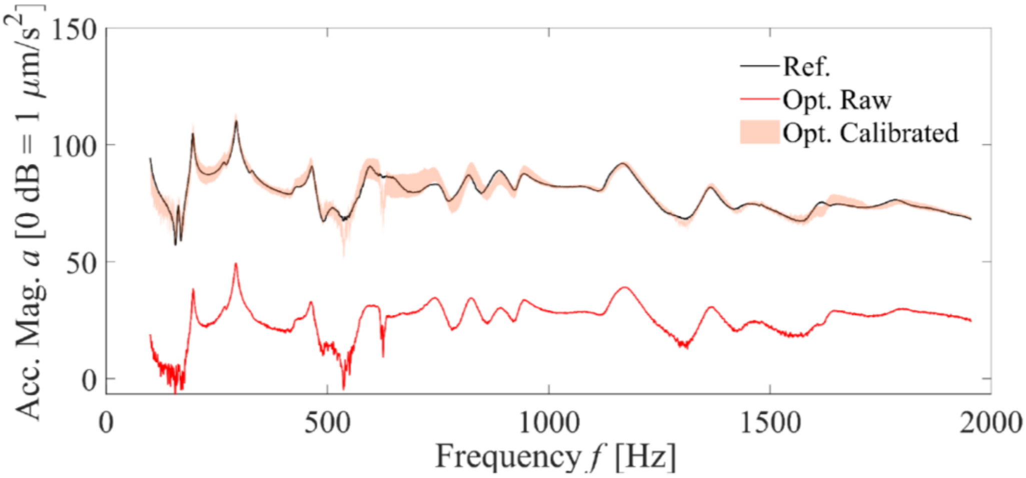

Figure 3: Average frequency spectrum of the acceleration magnitude a from the optical accelerometer (raw and calibrated results) at l = 600 mm, compared to the reference accelerometer. The excitation is an impulse from an impact hammer with peak force of 1.5 N ± 0.2 N. The experiment was repeated 18 times for each of the two accelerometers. The calibration is performed using the moving average and standard deviation technique for 200 frequency points

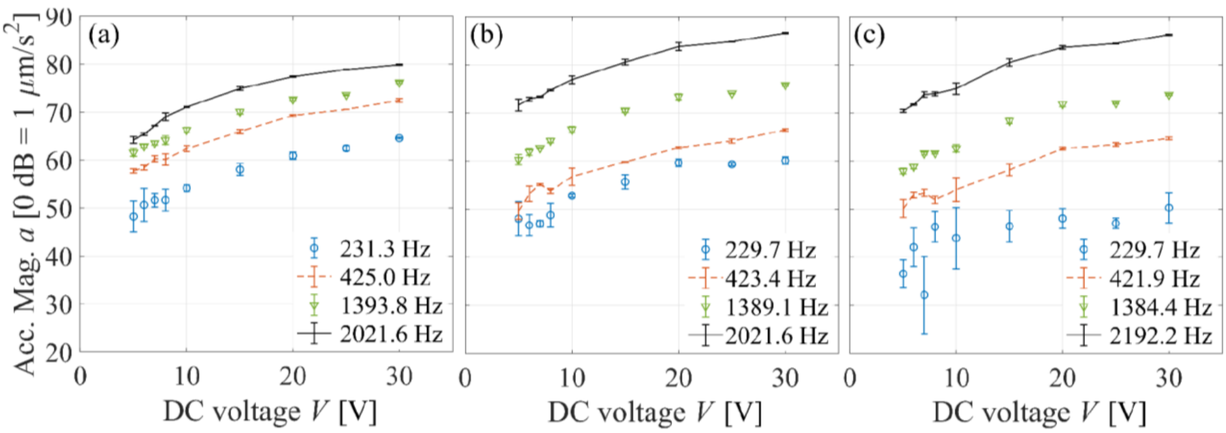

Figure 4: Peak values of the acceleration magnitude a at d = 400 mm at their respective frequencies obtained from the frequency spectrum at 90% threshold level, for screw length of (a) 0 mm, (b) 17 mm, and (c) 37 mm. The frequency values are provided in the legend to show the negligible variation. The accelerometer was placed at l = 400 mm from the support

The calibration has been done by using moving average of the difference between the two spectrums over linear 100-Hz frequency bands, as expressed in the following,

$$a_{OptC}(f) = a_{Opt}(f) + \sum_{n=-50}^{50} \frac{a_{ref}(f+n) - a_{opt}(f+n)}{100} \tag{1}$$

where $a_{Opt}(f)$, $a_{OptC}(f)$, and $a_{ref}(f)$ are the raw optical, calibrated optical and reference acceleration signals at frequency f, respectively. The standard deviation of the difference between the two spectrums, calculated for N = 18 repeats and indicated by the shaded area, is the largest at around 700 Hz to 800 Hz range (± 4 dB). This difference is less than 1 dB at other frequencies. This implies the measurements using the optical accelerometer matches well with those of the reference accelerometer. For the rest of this study, we use the frequency dependent calibration data shown in Fig. 3.

The micro-actuator device consisting of the board, a piezoelectric-patch and an attaching wood screw can be configured to excite a structure using different excitation levels. In Fig. 4, we show the results for three cases of screw lengths d = 0 mm (no screw attached), 17 mm, and 37 mm. For DC input voltage V to the board, we measured the vibration response at l = 400 mm in terms of acceleration magnitude a. The four largest peaks of the spectral power density of the acceleration response are considered to investigate the relation between vibration level and the input voltage. The changes of the frequencies of the peak values due to different configurations are negligible, as can be seen from the values in the figure legends.

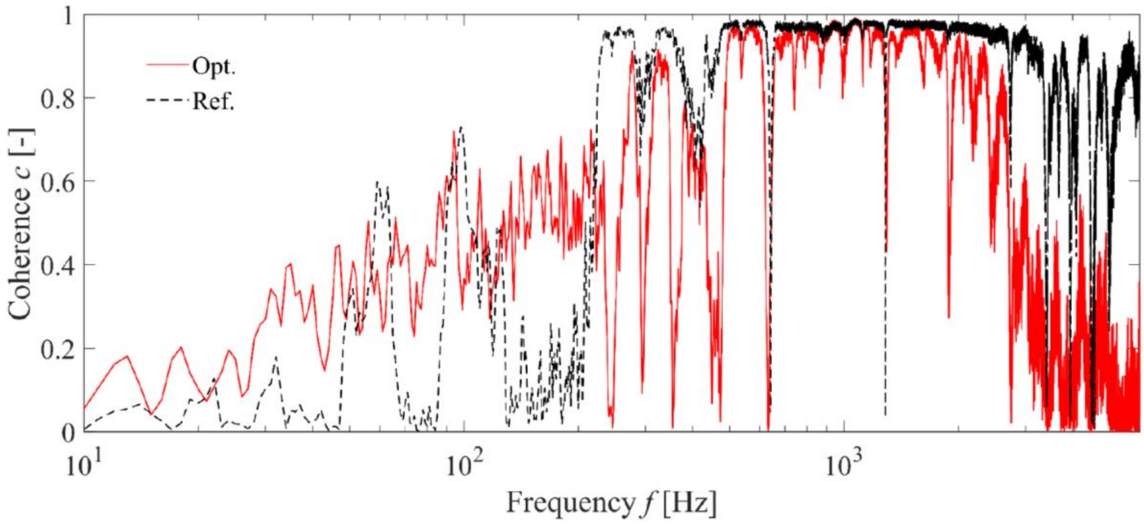

Figure 5: Coherence c of the measured acceleration up to 6,000 Hz at l = 600 mm due to an impulse excitation from the MiAC device at 18 V DC input to the board. The piezo-transducer was mounted at d = 37 mm (Fig. 4c). For these measurements, we used the same charge-mode accelerometer and only the connection to the DAQ was changed

For the three configurations, the response level (in dB) varies almost linearly with the input voltage. When no screw is used, the response level is between 50 to 80 dB for input voltage between 5 to 30 V. The range of the vibration level increases to 50 to 85 dB and 35 to 85 dB for d = 17 mm and 37 mm, respectively. This implies the screw playing an important role for mechanical transduction and can be used to control the excitation level and to achieve responses as small as 1 μm/s^2 and less. Finally, while comparing results from Fig. 4a to Figs. 4b-4c, it should be noted that the case of no screw (d = 0 mm) as a limit case differs from the other two cases since the transduction occurs over the larger area of the piezoelectric patch.

To investigate the performance of the calibrated optical accelerometer at relatively small vibration amplitude, the micro-actuator device with piezo-transducer is set up the same as the case d = 37 mm (Fig. 4c). The excitation signal is an impulse generated at DC input voltage of 18 V to the microcontroller board, corresponding to approximate electric current I = 0.04 A. A charge-mode accelerometer was placed at l = 600 mm, where the vibration level of less than 50 dB is expected (lowest level compared to the other two configurations). The connection between the DAQ and the accelerometer was first an optical fibre from the network and then changed to a typical accelerometer cable. All other conditions in these two experiments were kept constant. Fig. 5 shows the coherence c calculated from the two measurements. Throughout the 10 Hz to 100 Hz range, the coherence of measurements from the Ref. accelerometer is below 0.6. This is the same for the case of optical accelerometer; however, it performs better than the case of the Reference accelerometer for almost the whole range. This implies an optical accelerometer having a relatively better Signal to Noise Ratio (SNR) in this particular range for timber structures.

Between 100 Hz to 200 Hz, the Reference accelerometer provides almost incoherent measurements (c = 0) while the optical accelerometer gives stronger acceleration signal, almost linearly increasing up to c = 0.5. Between 200 Hz to 400 Hz, both accelerometers show a fluctuating coherence up to c = 0.8, with the optical accelerometer seemingly slightly underperforming compared to the charge-mode accelerometer. Between 400 Hz to 2,000 Hz, both sensors show good coherence levels (c > 0.8) for almost the entire range. Beyond 2,000 Hz, the coherence drops as the vibration level reduces, mainly due to natural attenuation in timber, to smaller than the minimum of the dynamic range of the two sensor setups (more significant for the optical accelerometer). Overall, the optical accelerometer demonstrates a better coherence below 2,000 Hz range for vibration analysis of timber structures, complementing the MiAC device for monitoring of low-amplitude vibration measurements.

4. CONCLUSION

We present a novel micro-actuator device consisting of a single layer piezoelectric transducer, a custom-built microcontroller and easy to mount transduction mechanism. This device is complemented by an accelerometer connected to an optical network for sensing low-amplitude vibrations in timber structure. The optical accelerometer was calibrated through comparison with a reference accelerometer showing an accuracy greater than ±1 dB. By controlling the length of the connecting wood screw, we increased the range of excitation level by 15 dB meaning longer connecting components provide lower vibration amplitudes of less than 1 μm/s^2. For the low amplitude excitation using the longer screw (d = 37 mm), we demonstrated the optical accelerometer provides better coherence below 200 Hz and similar coherence above 200 Hz compared to the reference accelerometer. However, the depth of screw and its connection quality as well as repeatability needs to be explored in more detail, and a follow up study is underway. Our preliminary results validate for the first time the applicability of our custom-build micro-actuator in combination with a new optical accelerometer that can be used for structural health monitoring of timber structures using low-amplitude vibrations.

5. AUTHOR CONTRIBUTION

SO: conceptualization, methodology, validation, experimental investigation, revision of manuscript, project administration, funding acquisition, visualisation. SS: methodology, software (signal processing), validation, experimental investigation, data curation, writing – original draft, writing – review & editing, visualisation. CN: methodology, validation, formal analysis, experimental investigation, writing – review & editing. ZB: investigation, data curation, visualisation, writing – review & editing. JL and TE: conceptualization, revision of manuscript.

TA, MM, RA, MK: revision of manuscript, project administration.

6. ACKNOWLEDGEMENT

This research is funded by Australian Research Council (ARC) Discovery Project No. DP 200100358 and ARC Linkage Project No. LP200301196. The authors would like to further thank colleagues and collaborators who contributed in a wider sense and over the years to make this research grow and happen (especially the device or the actuation as such, running through four prototypes since 2015) via discussions or direct technical assistance in particular Yaser Jazayeri Moghadas, Sophie Ho, Farzad Tofigh, Travers Sansom, and Ra Inta (in its early days using a beam-shaped piezo) and several student projects 4. references

6. ACKNOWLEDGEMENT

Brodzeli, Z, Nerse, C, Oberst, S (2022): Optical accelerometer/vibration sensor. PCT 20229029, 7 Oct 2022.

Brodzeli, Z, Silvestri, L, Michie, A, Guo, Q, Pozhidaev, E P, Chigrinov, V, Ladouceur, F (2013): Sensors at your fibre tips: a novel liquid crystal-based photonic transducer for sensing systems. *J. Lightwave Technol.*, **31**, 2940–2946.

Higuchi, T, Yamagata, Y, Furutani, K, Kudoh, K (1990): Precise positioning mechanism utilizing rapid deformations of piezoelectric elements. *In IEEE Proceedings on Micro Electro Mechanical Systems, An Investigation of Micro Structures, Sensors, Actuators, Machines and Robots*. 222-226.

Ishihara, H, Arai, F, Fukuda, T (1996). Micro mechatronics and micro actuators. IEEE/ASME *Transactions on Mechatronics*, **1**(1), 68-79.

Jebens, R, Trimmer, W, Walker, J (1989): Microactuators for aligning optical fibers. *Sensors and Actuators*, **20**(12), 65-73.

Oberst, S, Tofigh, F, Sepehrirahnama, S (2021): Bio-acoustic termite control device – laboratory experiments 20-IJ-11111136-040, Final Project Report - for US Department of Agriculture, 31 Aug 2021-29 (29 pages), University of Technology Sydney.

Palma, P, Steiger, R (2020): Structural health monitoring of timber structures – Review of available methods and case studies. *Construction and Building Materials*, **248**, 118528.

Tofigh, F, Sepehrirahnama, S, Oberst, S, Lai, J C S (2022): Characterising and calibrating piezo actuators for micro-excitation for vibration playback in bioassays of insects. *In Proceedings of 28th International Congress on Sound and Vibration*.