CHARACTERISING AND CALIBRATING PIEZO ACTUATORS FOR MICRO-EXCITATION FOR VIBRATION PLAYBACK IN BI-OASSAYS OF INSECTS

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Micro-vibration signals in bioassays under controlled environmental conditions in biotremology require a device that can generate a similar level of vibration response as caused by the insect. Since bioassays often need to be run in environmental cabinets, the space available is limited, and structures to be excited should not be mass loaded. Considering the properties of piezo actuators in generating very short strokes with high frequency and fast response times, stacked arrangements were found suitable for micro-excitation based on a given approximation of a Dirac delta impulse, approximating in the first instance the impact signal of a walking insect. However, at below the current limit of miniaturised force and displacement actuators, it is essential to characterise and calibrate the piezo actuators to ensure they are producing the desired signal at the point of contact on a given structure. Here we established a methodology for driving piezo actuators at the order of µm/s to generate low-amplitude impulsive excitations. The methodology includes finding the transfer function of the piezo actuator and an aluminum and a wood beam (Pinus radiata) of 20x10mm2 cross section and 200mm length. The reaction force from the piezo actuator was measured from about 40mN down to 2mN for travel ranges between 1.2µm and 11µm. The results showed that the force varies linearly from 5-19µm for the ceramic, and 0.6µm to 1.4µm for the PI and the MTK actuators with an input voltage ranging from 2-10V. The measurement setup improved using an anechoic chamber to reduce the noise level by one order of magnitude, compared to reported results in literature, and ensure excitation amplitudes as low as ±10nm/s can be measured. The presented methodology allows developing affordable micro-excitors in the future for playback bioassays in confined spaces which cause minimal mass loading on the test specimen.

Keywords: Micro-excitation, micro-Actuation, piezo actuators, biotremology, footstep vibration

1. Introduction

Vibrational communication (biotremology), as an ancient mode of communication, is widespread in arthropods, yet has rarely been studied in detail [1-3]. Among other modes of communication, such as chemical, tactile, and visual, many arthropods also rely on efficient and sophisticated information exchange via vibro-acoustics [4, 5]. Biotremology is used for foraging (food characterisation), the indication of threats, in eavesdropping in predator-prey, heterogenic (competing) or inquiline-host interactions, mating rituals, and directional sensing (vibro-klinotaxis) and localisation (vibro-phonotaxis), including Hymenoptera (ants, wasps, bees) and Isoptera (termites) [6-9]. Some insects, such as certain ants (*Acromyrmex lundi*) or termites have emerged to rely on vibro-acoustic communication, able to transmit and sense signals through complex substrate matter, with superb mechano-receptors for detection of minuscule vibration amplitudes in a noisy environment [10]. However, about the generation of microvibrations, especially as originated as a substrate response to a certain footstep pattern and its actuation is little understood [11].

Applications such as biomedical, aerospace, micro-optical and microfluidics systems, require a concise dealing with design, manufacturing, and packaging of micro systems [12-14] of high accuracy and precision. For all these applications, precision and positioning are the utmost important among researchers and manufacturing industries. The precise functionality of such systems requires fast response with stable motions and capability to offer a wide range of speed and load capacity [13, 14]. Wide range of actuators are used to achieve the required precision in actuation and position. Stepper motors along with gear drives and sliders are among the most favourable conventional methods of micro actuation and positioning systems [14-18].

In this study we aim to make the first step in developing a micro-actuating device to mimic the impulses of footsteps. To this end three actuators are purchased and validated for their ability to excite vibrations at the lower end of the scale of what is possible with standard miniature impact hammers, and vibration testing equipment. The actuators are tested for their linearity and robustness and compared in quality using experimental modal analysis. While much focus is set on eliminating noise and getting the boundary conditions right, the actual actuating kinematics and micro-mechanics as found in insect legs has been neglected.

2. Materials and methods

To achieve the desired precision and accuracy in design and manufacturing of the micro-actuator, a benchmark performance is required. To this end, a simple piezoelectric sensor/actuator, AB3342, along with two stacked micro actuators, PI841.10 from PhysikInstrumente [19] and MTK12S18f25000 from mechano-transformer [20], are tested and the performance are compared in terms of displacement, velocity, and force in vibration testing. An excitation signal is generated on a Raspberry PI 4 and translated into voltage using a 10 bit Digital to Analog converter. This signal runs through a simple amplifying circuit and then triggers the actuators. This inexpensive structure, as shown in Fig. 1(a), offers enough

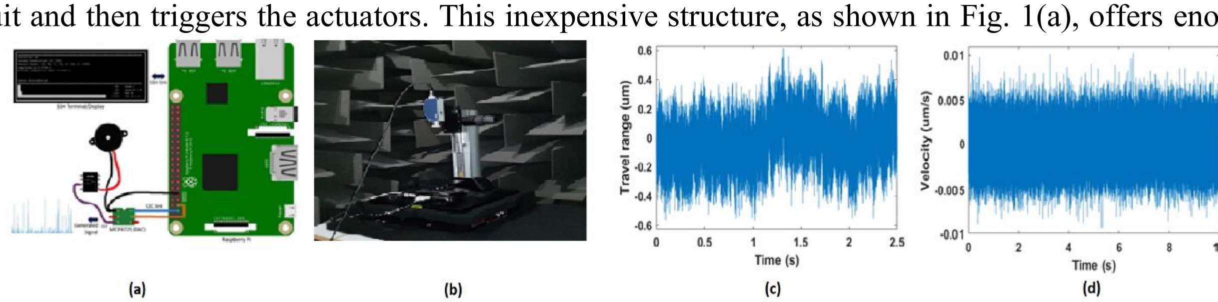

Figure 1: Setup of testing and characterisation of micro actuators, (a) diagram of the excitation system and the electronic parts; (b) the image of the experiment setup in the Anechoic room. A Laser Doppler Vibrometer (LDV) of type MSA050 is mounted on a stand; (c) Displacement and (d) velocity background noise levels.

flexibility to generate any desired signal, such as impulse (Dirac-delta), single triangle, sinusoidal, random, and artificial ant walking pattern [11], [21-23] as excitation signal [24].

All tests were conducted in an anechoic room to reduce the surrounding noise to the minimum possible level. For displacement and velocity measurements, Polytech MSA050 along with Polytec NLV-2500 with a vibration-isolation table is used. Considering the requirements of the experiments and as an extra layer of noise control, the setup is fixed on top of the layers of damping foams. Fig. 1(b) shows the setup in the anechoic room. Deployed experimental setup demonstrated promising noise control. Fig. 1(c) shows the recorded noise for the displacement signal with a maximum background noise measurement level of 0.4 µm using the MSA050. The noise level hence includes the channel noise (including electronic noise and signal distortion) but also measurement noise through the laser as well as environmental noise coming as residual contamination through the flooring and as airborne sound. Fig. 1(d) represents the maximum background noise level of 0.01 µm/s for a velocity measurement. Anechoic room temperature and humidity is monitored during the experiments. The temperature of the room was between 26 to 27 ºC, and the relative humidity level was around 40%.

3. Results

3.1 Characterisation of Piezoelectric Actuators

Experiments were initially started with a single impulse every four seconds to test the displacement of each actuator. The four second delay was applied to ensure that the whole system is in rest position when triggering the actuation. The maximum input voltage (as an impulse signal) was 10 V, and the minimum voltage was decided based on the displacement less than noise range (1.9 V). Fig. 2 illustrates the measurement results for all three actuators. As it can be seen the performance of all actuators are almost identical and linear. However, considering the noise level of 0.4 µm and very small travel range of actuators at 1.9 V, the linearity may not be seen clearly.

It is worthwhile to mention that response time of the actuators are also important in replicating the desired signal. Here, the response time refers to travel of an actuator head from the rest to the position corresponding to the input voltage, which can be measured from the rising edge of the peak in the velocity signal. During the tests, P-841.10 showed the fastest response time (1 ms) and the ceramic unit showed the slowest response time (3 ms). However, all actuators are reasonably fast in responding to the input signals for the micro-vibration applications.

3.2 Minimum measurable range of displacement

As discussed above, characterising the response of the actuators using displacement signal in lower voltage range (< 2 V) was nearly impossible due to the low signal-to-noise-ratio. Change to measuring the actuation velocity signal was the way to improve the SNR, which enabled us to investigate the response of actuators for input signals of below 2 V. The goal was to determine the smallest response that these actuators can produce. Fig. 3 represents such measurements of velocity for the three actuators. In

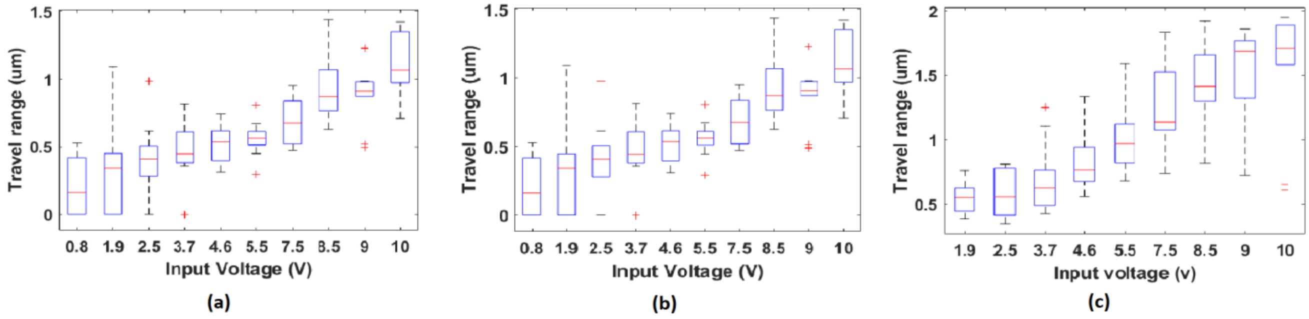

Figure 2: Displacement for three actuators (a) P-841.10; (b) MTK12S18f25000; and (c) AB3342.

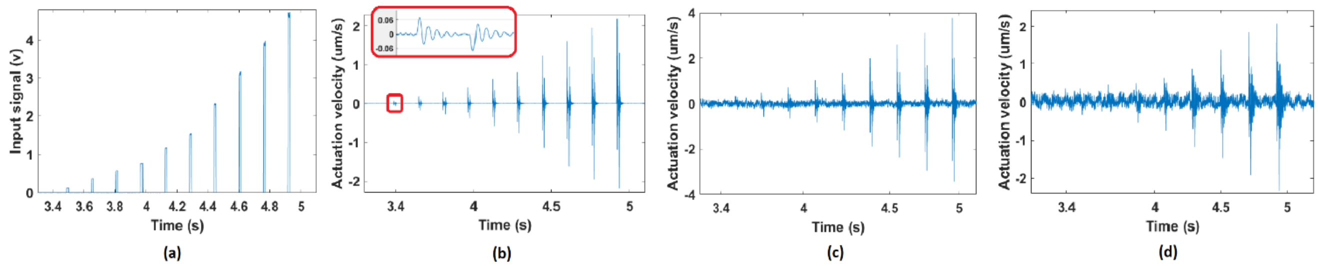

Figure 3: Velocity measurements (a) Input signal; (b) P-841.10; (c) MTK12S18f25000; and (d) AB3342.

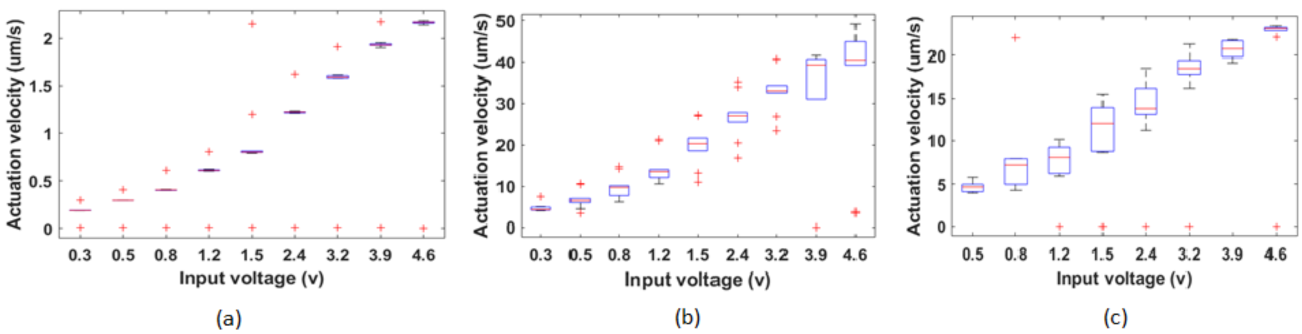

Figure 4: Linearity tests for the three actuators using the measured peak velocities for the voltage range of 0.3-4.6V for (a) P-841.10 (b); MTK12S18f25000; and (c) AB3342.

this set of tests, the voltage range of 0.3 V to 4.6 V that is lower than the previous 1.9 V to 10V was applied on the actuators. Actuator P-841.10 shows the best results on the noise level which enables detecting actuation at 0.3 V with the velocity of (0.06 µm/s). The ceramic piezoelectric is the noisiest one which makes the minimum voltage of 0.8 V with the velocity of (4 µm/s). The double oscillation that can be seen on the measurements are due to the collision of the micro-impact hammer with the actuator.

Fig. 4 indicates the statistical results of 10 actuation response in terms of velocity for the three devices. These were obtained by using the input signal with 10 impulses, like Fig. 3a, ranging from 0.3 V to 4.6 V. In terms of the peak velocities, it was found that all transducers exhibit an S-shaped response for the given voltage range. However, its deviation from the linear regression of the mean values is negligible. The measured SD values are indicators of the response reliability, which can be used as a quantity of actuation performance. Considering the SD range, P-8421.10 is the most reliable (Fig. 4a) in terms of producing the same response to a fixed input voltage, while the least reliable is the ceramic actuator (Fig. 4b). Repeating these experiments, provides the chance of studying the linearity of the actuation velocity in all three actuators.

3.3 Force Measurements for the Piezoelectric Actuators

Force measurements are one of the critical parts of designing the micro-actuation device as it aims to reproduce the walking pattern of an insect. In this series of experiments, a B&K 8203 micro-impact hammer with sensitivity of 0.5 mN was used in sensing mode. In this approach the tip of the hammer touches the tip of the actuator so the actuator can easily trigger the force sensor with very small movement, as shown in Fig. 5. Although the noise level for various actuators can be different, the average of the noise level of 0.4 mN for force measurements were recorded. The actuation force according to the input voltage is measured to understand the possibility of force control in replicating the desired signals. As it is shown, the best possible minimum measurement was recorded as 0.5 mN. However, detecting the signal is quite challenging and can be mistaken for noise especially if the excitation signal is not available.

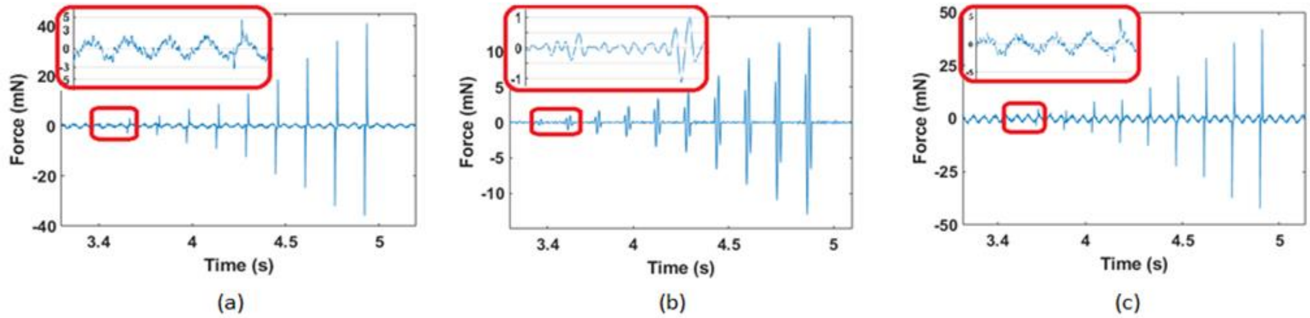

Figure 5: Force measurements (a) P-841.10; (b) MTK12S18f25000; and (c) AB3342.

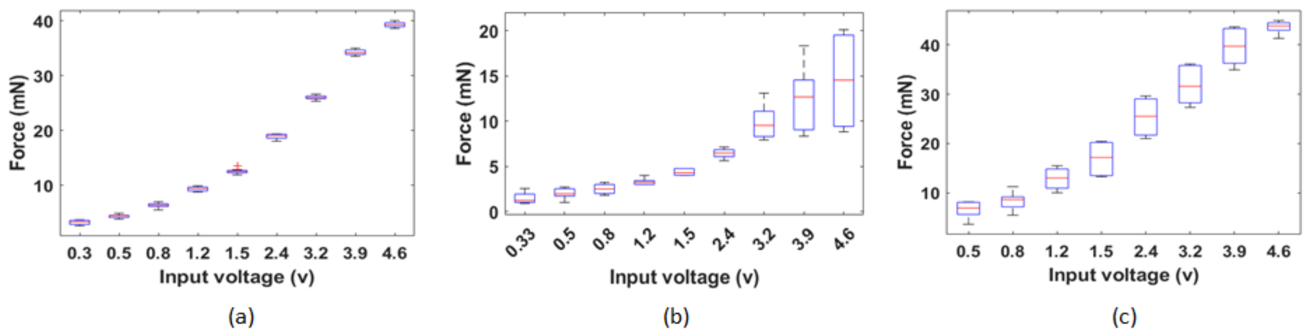

Figure 6: Linearity tests for the three actuators using the measured peak force for the voltage range of 0.3-4.6V for (a) P-841.10; (b) MTK12S18f25000; and (c) AB3342.

Fig. 6 indicates the results of actuation force response for the three actuators. These were obtained by using the input signal with 10 impulses, like Fig. 3a, ranging from 0.3 to 4.6V. In terms of the peak force, it was found that all transducers exhibit an S-shaped response for the given voltage range. However, its deviation from the linear regression of the mean values is negligible. As mentioned, the measured SD values are indicators of the response reliability, which can be used as a quantity of actuation performance. Considering the SD range, P-8421.10 is the most reliable (Fig. 6a) in terms of producing the same response to a fixed input voltage, while the least reliable is the ceramic actuator (Fig. 6b). Repeating these experiments, provides the chance of studying the linearity of the actuation force in all three actuators.

3.4 Transfer function of Piezo actuators

Biotremology requires a device that can generate a similar level of vibration response as caused by the insect. However, the only controllable factor in this process is the input signal of an actuator. So, the transfer function of each actuator needs to be extracted to ensure accurate vibration response. To this end, the coherence of the response with respect to the input voltage is investigated. Fig. 9 shows the coherence of the response with respect to the input voltage in each of the actuators.

Figure 7 shows the frequency response functions of the three transducers for an impulse driving signal. The coherence results show a high fidelity between the response and the input signal for all the transducers in the range of 1 kHz to 10 kHz. Below 1 kHz, P-841 and MTK transducers are more reliable than the ceramic transducer AB3342. These frequency response functions, both magnitude and phase data, can be used to adjust the voltage signal according to a given arbitrary signal such as the ant-walking pattern signal.

Figures 8 and 9 show the frequency response functions of the aluminium and wood beam specimens that are excited by the three transducers. The input voltage signal is a single impulse in a 2 s time span with the magnitude of 8V. These measurements are conducted for three points and the results are shown for the point that is furthest in length from the point of excitation. The sampling frequency for the FFT was 25.6 kHz, which led to 1 Hz frequency resolution. For the aluminium beam, a strong coherence can be

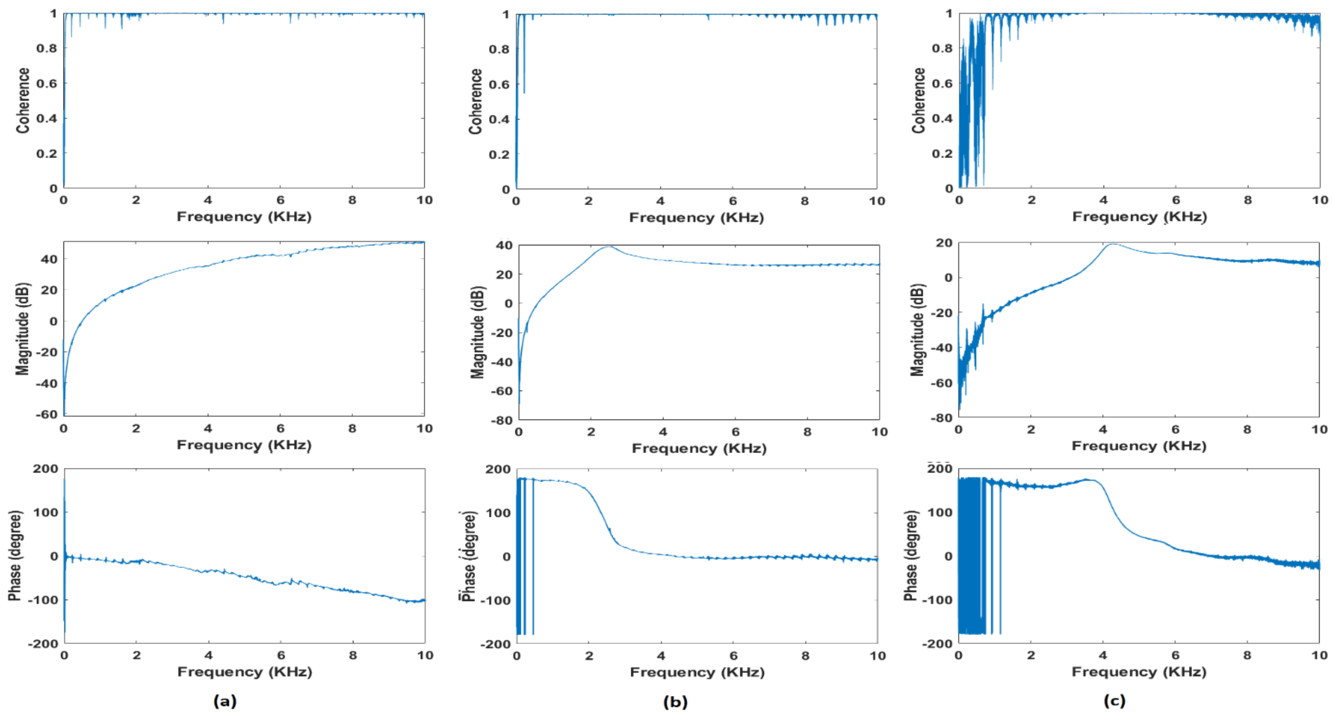

Figure 7: Coherence and frequency response function of the three actuators using the measured acceleration vs. voltage (a) P-841.10; (b) MTK12S18f25000; and (c) AB3342.

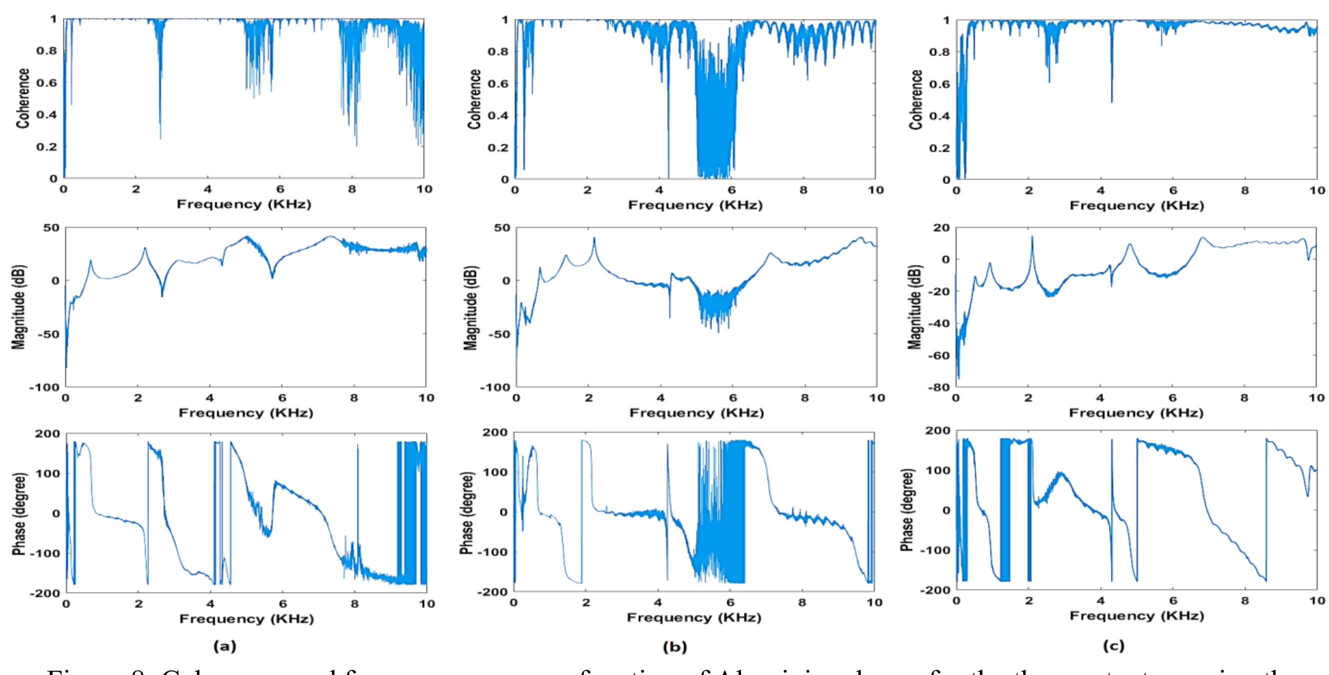

Figure 8: Coherence and frequency response function of Aluminium beam for the three actuators using the measured acceleration vs. voltage (a) P-841.10; (b) MTK12S18f25000; and (c) AB3342.

seen for the case of P-841 transducer in the entire frequency range, except for 2.5 kHz, 5-6 kHz, 7-8 kHz, and 8.5 to 10 kHz. The worst performance in terms of signal coherence was from the MTK transducer, with coherence value of above 0.65 threshold for most of the frequency range, except the 5-6 kHz range. The best performance was from the ceramic transducer with strong coherence of above 0.8 for almost all the studied frequency range. The difference between the magnitude results of the frequency response functions is due to the efficiency of the transducer design in converting electrical signals to mechanical motion, within their transduction range. This can be seen that ceramic transducers show lower magnitude

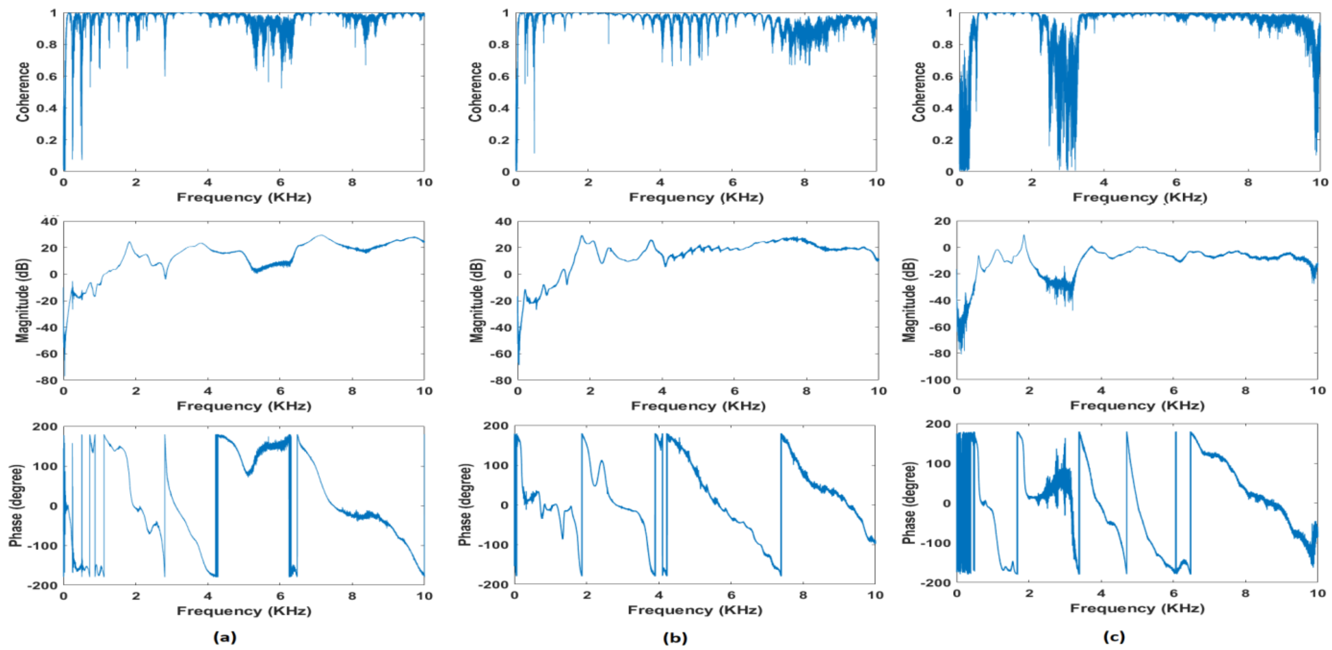

Figure 9: Coherence and frequency response function of Aluminium beam for the three actuators using the measured acceleration vs. voltage (a) P-841.10; (b) MTK12S18f25000; and (c) AB3342.

as compared to P-841 and MTK which both have similar range in their magnitudes of the frequency response function. For the wood beam, similar coherence results were observed for P-841 and MTK transducers, considering the 0.65 threshold. For the ceramic transducer, a strong coherence was obtained across the frequency range, except for 2 kHz to 4 kHz range. As expected, the measured response of the aluminium beam was much stronger than the wood beam by 10 dB at the largest peak. The differences in the frequency response functions of the two beam specimens includes the transducers response functions and the condition of contact and friction between the moving tip of the transducers and the point of impact.

4. Conclusions

We presented the characterisation of three different piezoelectric actuators for micro-vibration testing. A setup was designed and placed in an anechoic room for the tests, and significantly low noise levels of 0.6 μm displacement and 0.01 μm/s velocity were achieved. The linearity of the transducers' responses within their working range of voltage was measured and compared against each other. It was found that the ceramic transducer which is simpler in design and a cheaper alternative can be used for actuation as small as 2 μm. Frequency response functions of the transducers were obtained for adjusting the voltage signal according to a given actuation signal such as ant-walking pattern. All the transducers showed a strong and coherent response in their range of operation. Finally, the transducers were used to obtain the frequency response function of two beam specimens. This approach of rigorous characterisation allows these transducers to be used for micro-vibration testing beyond the current capacity of impact hammers, for a long period of time, and minimising human errors in generating robust and high-fidelity excitation signals with simple electronic equipment.

REFERENCES

1 Cividini, S., Montesanto, G. *Biotremology in arthropods*. Learn Behav 48, 281–300 (2020)

2 Peggy S.M. Hill, Andreas Wessel, Biotremology, Current Biology, Volume 26, Issue 5 (2016)

3 Virant-Doberlet Meta, Kuhelj Anka, Polajnar J., Šturm R., *Predator-Prey Interactions and Eavesdropping, Frontiers*, Ecology and Evolution, vol 7 (2019)

4 Beth M., *Biotremology: Do physical constraints limit the propagation of vibrational information?*, Animal Behaviour, Vol 130 (2017)

5 Johannes S., Nataša S., Rachele N., Meta V., Valerio M., *Chapter Four - Communication by substrate-borne mechanical waves in insects: From basic to applied biotremology*, Editor(s): Russell J., Advances in Insect Physiology (2021)

6 Evans T.A., Inta Ra, Lai J.C.S., Prueger S., Foo N.W., Fu E.W. and Lenz M., *Termites eavesdrop to avoid competitor-s*Proc. R. Soc. B.2764035–4041 (2009)

7 Oberst S., Lai J. C. S. and Evans T. A., *Key physical wood properties in termite foraging decisions*, J. R. Soc. Interface.152018050520180505 (2018)

8 Oberst S., Lenz M., Lai J. C. S. and Evans T. A., *Termites manipulate moisture content of wood to maximize foraging resources*, Biol. Lett.152019036520190365 (2019)

9 Masoni, A., Frizzi, F., Nieri, R. et al. *Ants modulate stridulatory signals depending on the behavioural context*. Sci Rep 11, 5933 (2021)

10 Evans T.A., Inta Ra, Lai J.C.S., Prueger S., Foo N.W., Fu E.W. Lenz M., *Termites eavesdrop to avoid competitors, Proc*. R. Soc. B.2764035–4041 (2009)

11 Oberst, S., Bann, G., Lai, J.C., Evans, T.A., *Cryptic termites avoid predatory ants by eavesdropping on vibrational cues from their footsteps*, Ecol Lett, 20: 212-221. (2017)

12 Hsu T-R, *MEMS and Microsystems: Design and Manufacture*, USA: McGraw-Hill (2004)

13 Maluf N and Williams K, *An Introduction to Microelectromechanical Systems Engineering*, Artech House Inc (2002)

14 Lin X, Chen H, Ma Y, Fisher J G, Huang S, Zhang D and Cheng X 2017 *Investigation of temperature sensitivity of 28 Smart Mater. Struct. Topical Review actuation performance for piezoelectric fiber composites Ceram*., Int. 43 (2021)

15 Gardner J W, Varadan V K and Awadelkarim O O, *Microsensors MEMS and Smart Devices*, England: Wiley (2001)

16 Tzou H S, Lee H J and Arnold S M, *Smart materials, precision sensors/actuators, smart structures, and structronic systems*, Mech. Adv. Mater. Struct. 11 367–93 (2004)

17 Liang C, Wang F, Shi B, Huo Z, Zhou K, Tian Y and Zhang D, *Design and control of a novel asymmetrical piezoelectric actuated microgripper for micromanipulation*, Sensors and Actuators A, 269 227–37 (2018)

18 Xiao X, Li Y and Xiao S, Development of a novel large stroke 2-DOF micromanipulator for micro/nano manipulation, Microsystem Technologies, 23 2993–3003 (2017)

19 [Online.] available: https://www.physikinstrumente.com/en/products/piezoelectric-transducers-actuators/p-841-pre-loaded-piezo-actuators-412418452/

20 [Online.] available: https://www.mechano-transformer.com/products/mechatrans/mtk.php

21 Oberst S, Lim S, Romão AC, Lai JCS, Stender M, Hoffmann NP, Evans TA, *A coupled mono-bipedal biomechanical surrogate model to mimic ants walking and running gait analysed using recurrence plot quantification analysis*, Colloquium on Irregular Oscillations and Signal Processing, Hamburg, Germany, 10-12 Sep (2018)

22 Oberst S, Lai, JCS, Evans TA, *Excitation signal extraction of ant walking pattern under the influence of noise using a biomechanical bipedal mathematical model*, 2nd International Symposium on Biotremology, Riva del Garda, Italy, 4-6 Sep July (2018)

23 Oberst S, Nava-Baro E, Evans TA, Lai JCS, *An innovative signal processing technique for the extraction of ants' walking signals*, Acoustics Australia, 43(1) 87-96 (2015)

24 Oberst S, Lai JCS, Evans TA, *Physical Basis of Vibrational Behavior – Channel Properties and Noise*, Biotremology: Studying Vibrational Behavior, Springer International Publishing, Heidelberg New York, Germany. (2019)

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