Chapter 8
Inexpensive Methods for Detecting and Reproducing Substrate-Borne Vibrations: Advantages and Limitations

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Abstract There is increasing appreciation of the role of vibration-mediated interactions among animals, and between animals and plants. However, growth of the field is limited by the widespread assumption that this research requires expensive, specialized equipment for detecting and reproducing vibrations. In this chapter, we demonstrate that this assumption is not entirely justified for plant-borne vibrations. We compare the performance of industry-standard equipment for vibration recording and playback with inexpensive alternatives. For conducting high-fidelity playback experiments, there is no difference in the performance of actuators that vary a thousand-fold in price, as long as the appropriate software is used. For obtaining accurate recordings of plant-borne vibrations, the utility of the low-cost alternative sensors we tested is constrained by their frequency response, which is not flat and which can vary between measurements. These readily available sensors are thus primarily useful for detecting and monitoring vibrational signals, rather than for quantitative description or for conducting playback experiments. However, although inexpensive alternatives do not replace calibrated vibration sensors for quantifying the physical properties of signals, they do open up new possibilities for investigation, such as characterizing natural vibrational soundscapes using many sensors at once.

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8.1 Introduction

The number of animal taxa that use substrate-borne mechanical waves to communicate is substantial, particularly among invertebrates. The percentage of species relying on vibrational communication is estimated to be 90% among insects and even higher among spiders (Barth 2002; Cocroft and Rodriguez 2005). Plants also perceive mechanical stimuli (Braam 2004; Telewski 2006) and have recently been found to respond appropriately to incidental vibrations produced by feeding herbivores or flying pollinators (Appel and Cocroft 2014; Body et al. 2019; Veits et al. 2019). However, despite the widespread use of mechanical waves as signals in nature (Hill and Wessel 2016), the study of how vibrations influence biotic interactions remains limited by access to suitable equipment for recording and playing back vibrations.

For vibrational stimuli, the “gold standard” devices for recording are laser Doppler vibrometers, which allow non-contact measurement of the velocity of a moving surface. The other standard sensors are accelerometers, which measure acceleration when in contact with a moving surface. Lasers and accelerometers provide repeatable measurements that (with appropriate data acquisition hardware and software) can be expressed in real-world units of velocity and acceleration. Laser vibrometers are costly sensors, on the order of tens of thousands USD, and individually calibrated accelerometers are less costly but still on the order of a thousand USD. In contrast, more inexpensive vibration sensors include phonograph cartridges and piezoelectric disks or film, among others. Piezo disks, which typically cost less than 1 USD, have been used very successfully for detection and control of insect pests on large woody hosts (Dunn 2006; Mankin 2019) and they may be useful for a wider variety of applications. We also test one relatively inexpensive accelerometer (less than 100 USD) that has been used for vibrational communication research (e.g., Cocroft 1999) and which has a flat frequency response over a range useful for many substrate-borne insect signals.

For reproducing vibrations, the “gold standard” device is the mini-shaker, which is constructed like a speaker with a moving coil and magnet but designed to couple the vibration to a solid structure rather than to the air. Most mini-shakers are also relatively expensive, on the order of thousands of USD. A variety of inexpensive devices have also been used for reproducing vibrations, including loudspeakers modified to reduce airborne sound and to couple the speaker motion to a surface, electromagnets that drive a magnet attached to a surface, and piezoelectric disks. The advantages and disadvantages of inexpensive vibration sensors and actuators have been little explored in the literature.

In this chapter, we conduct playbacks and recordings to illustrate the advantages and disadvantages of several inexpensive methods for vibration recording and playback. Our survey is not exhaustive but instead focuses on several devices that are readily available. As a standard for comparison, we use a laser vibrometer or calibrated accelerometer for recording, and a Brüel & Kjær mini-shaker for playback. Our aim is to provide a non-exhaustive list of inexpensive tools that can be used to investigate the role of vibrational signals in a growing number of taxa and contexts. Because our research deals mainly with plant-dwelling insects and plants, the focus of this study will be on small animals using plants as a substrate. However, many of our considerations can be applied to larger-scale systems. For playbacks, we first demonstrate that the use of an expensive device is not sufficient for conducting high-fidelity playback experiments, providing a cautionary note against uncritical use of the equipment. We then show that inexpensive alternatives perform equally well in reproducing plant-borne vibrations. For sensors, we show that while inexpensive sensors are suitable for detecting and monitoring vibrational signals, their limitations include the lack of a flat frequency response and a lack of consistency in the output. As a result, while high-fidelity vibrational playbacks can be done with readily available and inexpensive devices, access to a calibrated vibration transducer such as an accelerometer is still necessary for studies in which precise control over the stimulus is needed. On the other hand, the availability of inexpensive, easily replaced vibration sensors opens up a new range of research avenues.

8.2 Is Use of an Industry-Standard Device Sufficient for Reliable Playbacks?

To conduct a reliable playback experiment, the experimenter needs adequate control over the properties of the played-back signal so that, for example, the characteristics of a played-back natural signal match those of the original recording. The primary way that playback experiments fail to achieve this goal is that the played-back signal differs from the original in its frequency spectrum and its amplitude (Cocroft et al. 2014). Better control over the experimental stimulus requires that the researcher calculate the filter imposed by the playback system, design a compensation filter, and adjust the amplitude of the pre-filtered stimulus. Software for achieving these tasks is available (Michael et al. 2019). We first show that simply recording a signal and playing it back is not sufficient, even when using a laser vibrometer and a shaker. We also show that a given compensation filter is accurate only for the location on the plant where it was calculated, and only until the shaker is detached from the substrate, even if it is replaced in the same location.

8.2.1 Mini-Shaker: Methods

The experimental setups for comparing playback and recording devices are shown in Fig. 8.1. For testing the mini-shaker (Type 4810, Brüel and Kjær Sound & Vibration A/S, Nærum, Denmark) and other playback devices, we chose three stimuli representative of those used in playback experiments on plants: band-limited noise (50–10,000 Hz); an advertisement signal of the treehopper *Umbonia crassicornis*

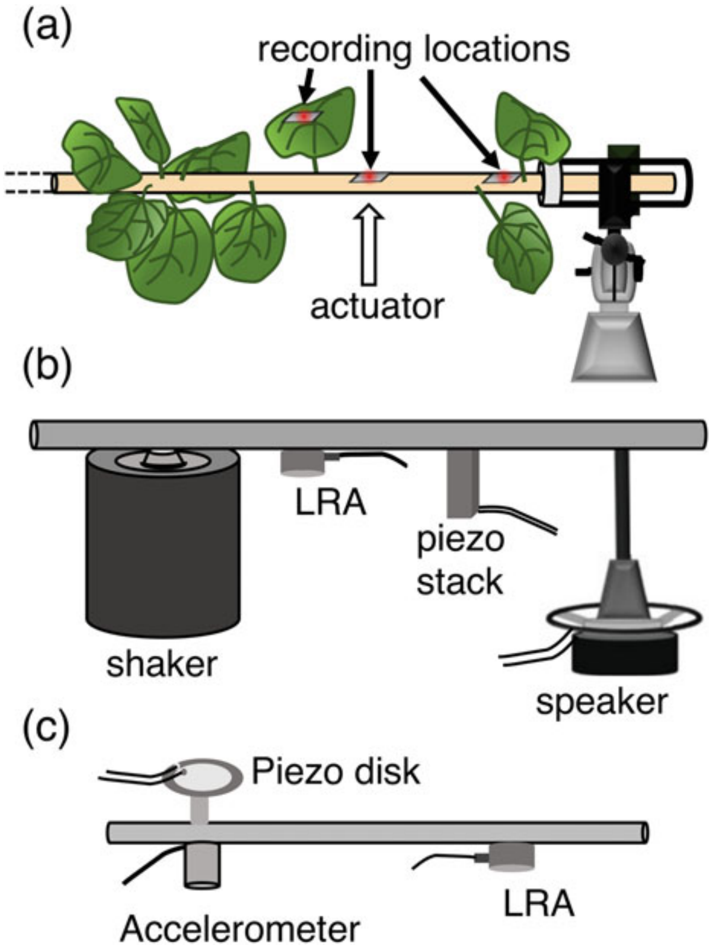


Fig. 8.1 Experimental apparatus used for recording and playback: (**a**) setup for testing playback devices; (**b**) playback devices; (**c**) setup for testing sensors

(Hemiptera: Membracidae) recorded on the stem of a woody host, *Albizia julibrissin* (Mimosaceae); and vibrations produced by a caterpillar, *Vanessa cardui* (Lepidoptera: Nymphalidae), feeding on a soybean leaf (Fabaceae: *Glycine max*). The male signal and the feeding vibrations were recorded with a laser vibrometer (PDV-100, Polytec Inc., Auburn, MA, USA). The mini-shaker was driven from the computer via an amplifier (Behringer HA8000 8-channel High-Power Headphones Mixing and distribution amplifier, Behringer USA, Bothell, WA USA). To record the vibrations produced by the mini-shaker, the laser signal was sent to an audio interface (Celesonic US-20x20, Tascam, TEAC America Inc., Santa Fe Springs, CA USA) whose inputs we calibrated using a Tenma 72-2580 digital oscilloscope (Newark Element 14, Chicago, IL, USA).

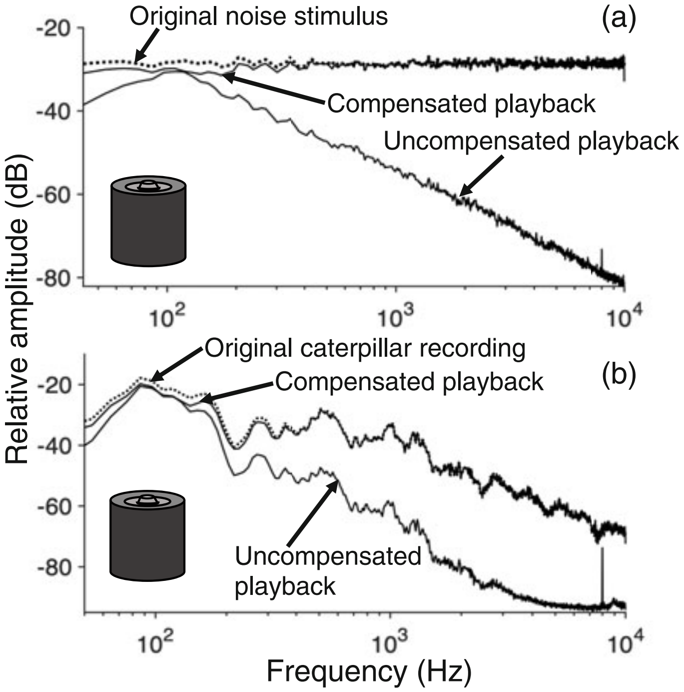
We performed the compensation-and-calibration step using the Matlab (Mathworks, Natick, MA USA) script described in detail by Michael et al. (2019), which is free and available online. We used a frequency range of 50–10,000 Hz for designing the frequency filter. The target amplitudes for the playbacks were set to match the peak velocity of the original signals: 0.4 and 3.5 mm/s for the *U. crassicornis* male call and the *V. cardui* feeding vibrations, respectively. The target amplitude for the white noise was arbitrarily set at 1 mm/s.

We tested the mini-shaker when it was unloaded and when it was attached to a plant stem. The plant stem was a 45-cm-long branch cut from a *Hibiscus* sp. and placed in a water tube (stem diameter at the attachment site 5 mm). To couple the plant stem to the shaker, which remained in an upright position on the vibration table, we positioned the stem horizontally using clamps so that it lightly but securely contacted the tip of a metal screw attached to the mounting stud of the shaker. We added a small quantity of wax between the stem and the screw. We measured plant vibration in three locations (Fig. 8.1a): on the stem immediately opposite the site of attachment to the shaker; on the stem 10 cm from the attachment site; and on a leaf whose petiole attached to the stem 2.5 cm from the mini-shaker.

8.2.2 Mini-Shaker: Results and Discussion

There is a basic mismatch between a laser vibrometer and a mini-shaker: the shaker is designed to have a flat frequency response with respect to acceleration, while the laser's output is proportional to velocity. Accordingly, a laser recording of broadband noise played back through a shaker will show the expected 6 dB/octave falloff (Fig 8.2a). So while it would seem straightforward to record an insect signal with a laser vibrometer and play it back with a mini-shaker, the played-back signal will differ substantially from the original (Fig 8.2b). This mismatch can be corrected with a compensation filter, however, and the resulting signal closely matches the original (Fig. 8.2a, b).

Fig. 8.2 Amplitude spectra illustrating the performance of the mini-shaker with and without pre-filtering of the stimulus using a compensation filter. Stimuli were (**a**) band-limited noise and (**b**) feeding vibrations of a butterfly larva (*Vanessa cardui*)



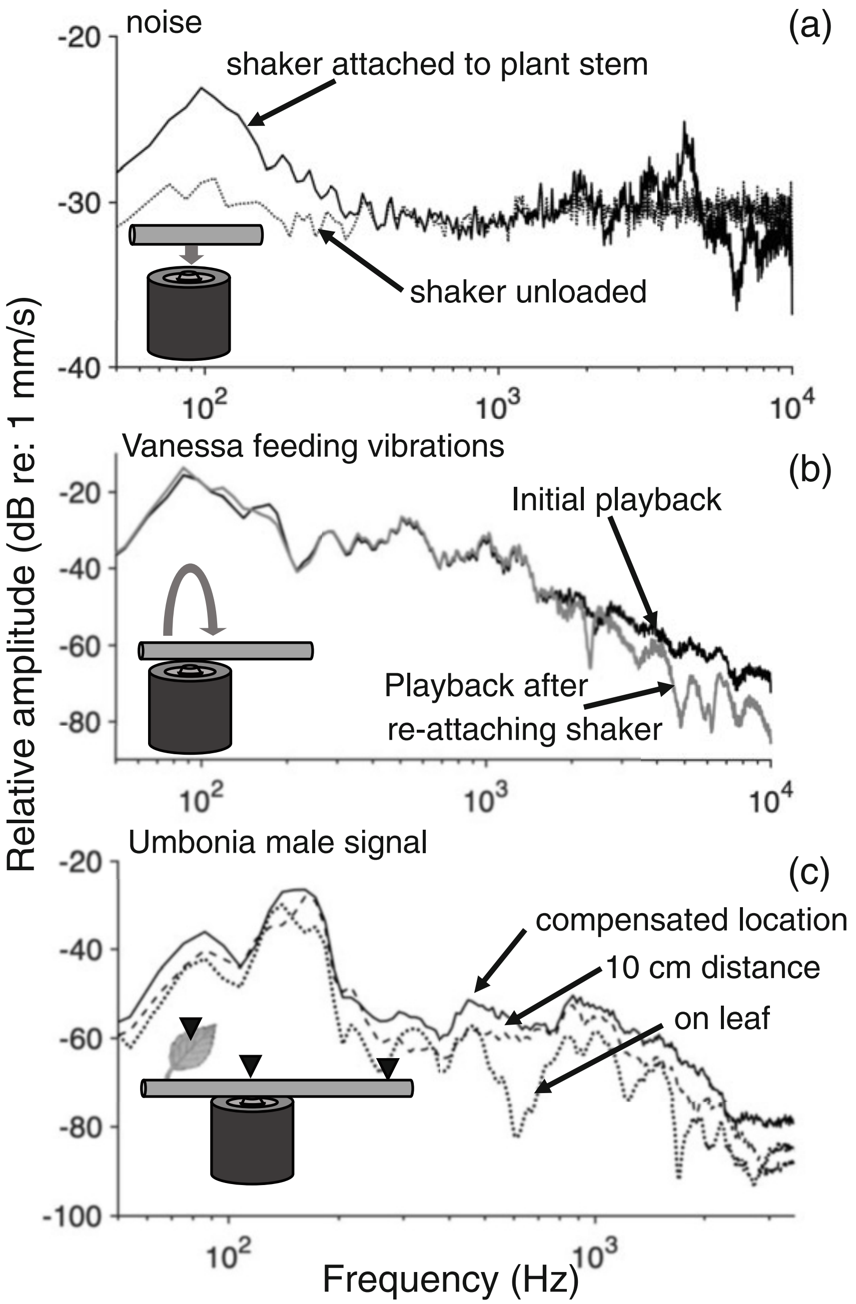


Fig. 8.3 Amplitude spectra illustrating the effect of (**a**) adding a load to the shaker without calculating a new compensation filter; (**b**) detaching and re-attaching the mini-shaker without calculating a second compensation filter and (**c**) recording the stimulus at the location of the mini-shaker and at two other locations on the plant stem

Once the shaker is attached to a substrate, in this case a plant stem, a new compensation filter is needed (Fig. 8.3a). Furthermore, for precise control over the stimulus, this filter must be re-calculated each time the shaker is detached from and re-attached to the substrate, even if it is re-attached in the same location (Fig. 8.3b).

And note that this compensation filter is only accurate for the location where it is calculated; once the signal propagates through the plant, it will be subject to additional filtering (Fig. 8.3c).

8.3 Alternative Playback Devices

A variety of devices have been used as actuators for vibrational playback experiments. These include not only the mini-shaker described above, but also small speakers modified as described in Michael et al. (2019), linear resonant actuators (LRAs; Losinger 2016), piezoelectric actuators (Appel and Cocroft 2014), and piezoelectric disks (Mankin 2019). Our goal was to illustrate the utility of a range of playback devices with costs ranging from less than 1 USD (piezoelectric disk), less than 10 USD (LRAs), less than 1000 USD (piezoelectric actuator and driver) to well over 1000 USD (mini-shaker).

8.3.1 Playback Devices: Methods

We used the same plant stem as with the mini-shaker to examine the output of four other devices: two sizes of LRAs (8 mm × 3.2 mm, 9 mm × 3.4 mm; Fyber Labs, Inc., Kirkland, WA, USA); an 8-ohm speaker modified as described in Michael et al. (2019); and a piezoelectric actuator (Thorlabs AE0505D18F actuator; Thorlabs, Inc., Newton, NJ, USA). To drive the LRAs and speaker we used the Behringer HA8000 amplifier, and for the piezoelectric actuator we used a Thorlabs MDT693B controller.

We used wax to attach the LRAs and to secure the attachment between the piezoelectric actuator and modified speaker to the stem. The piezoelectric actuator was supported on a magnetic base stand, and the speaker was placed directly on the anti-vibration table. We tested each playback device using the same playback files and setup we used for the mini-shaker (Fig. 8.1a, b).

8.3.2 Playback Devices: Results and Discussion

Although the playback devices differed greatly in size, design, and cost, all were capable of matching the desired frequency spectrum to within ±3 dB over a 65–10,000 Hz range (Fig. 8.4a; the LRA 9 mm and the modified speaker exceeded that deviation at 50 Hz). All of the devices also successfully reproduced the insect-generated vibrations (Fig. 8.4b, c), with an average deviation from the original recording of ≤ 1 dB and maximum deviations of ±3 dB with the exception of the 9 mm LRA (maximum deviation of 5 dB) and the modified speaker (maximum

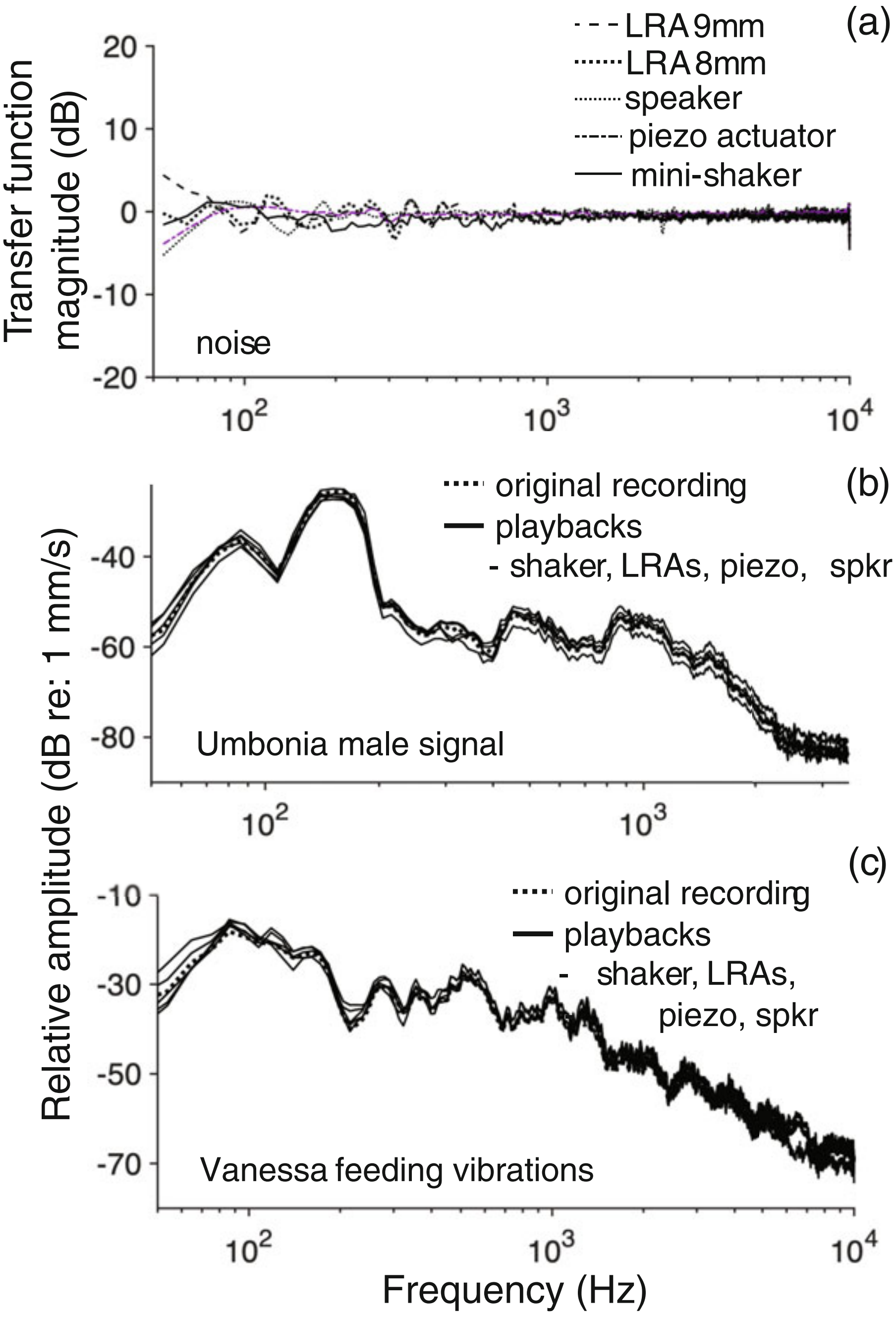


Fig. 8.4 Relative performance of the five tested playback actuators: (**a**) transfer function between original noise stimulus and the five actuators, each of which received its own compensation filter; (**b**) amplitude spectra of the original recording of a treehopper signal and playbacks of that signal using each of the five actuators; (**c**) amplitude spectra of the original recording of caterpillar feeding vibrations and playbacks of that recording using each of the five actuators

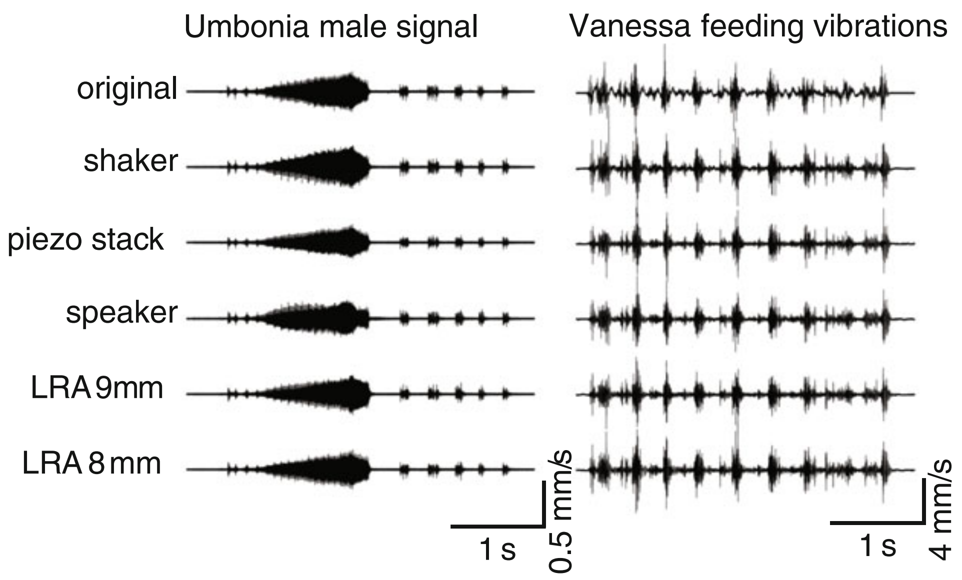


Fig. 8.5 Waveforms of the treehopper signal and caterpillar feeding vibrations, including the original recording and compensated playback of that recording with the five actuators

deviation of 4 dB). Examination by eye of the waveforms of the played-back signals (Fig. 8.5) suggests that qualitatively, the waveforms produced by the shaker and the LRAs were most similar to the original, while the waveform produced by the modified speaker (at least for the *Umbonia* male signal) was less similar to the original. However, cross-correlating the original waveform with the recorded playbacks of the *Umbonia* signal does not support this impression; the cross-correlation coefficients, standardized to a maximum of 1.0, were: shaker (0.94), piezoelectric stack (0.91), modified speaker (0.95), LRA 9 mm (0.95), LRA 8 mm (0.97). In spite of the 1000-fold cost difference between an LRA and a mini-shaker, then, for purposes of reproducing an insect mating signal on a plant, the two are equivalent.

8.4 Inexpensive Vibration Sensors

The industry-standard methods for measuring vibration are laser vibrometers and accelerometers. However, there are a multitude of ways of converting mechanical vibrations into electrical signals. Among the many methods that have been used in studies of vibrational communication are phonograph cartridges (Henry et al. 1999), loudspeaker membranes (Moraes et al. 2005), and piezoelectric disks (Mankin 2019). Piezoelectric disks have been incorporated into an apparatus for detecting insect vibrations in trees with high sensitivity and low noise (Dunn 2006), and this work has led to new methods of controlling the behavior of harmful insects (Hofstetter et al. 2019). New methods for vibration detection continue to be developed, such as computer vision processing of high-speed audio (Davis et al. 2014).

Here we compare the output of an individually calibrated accelerometer with the output of three sensors: a 2.7 cm piezo disk, a ceramic-element phonograph cartridge, and a Knowles BU-1771 accelerometer (Knowles Electronics LLC, Itasca, IL, USA).

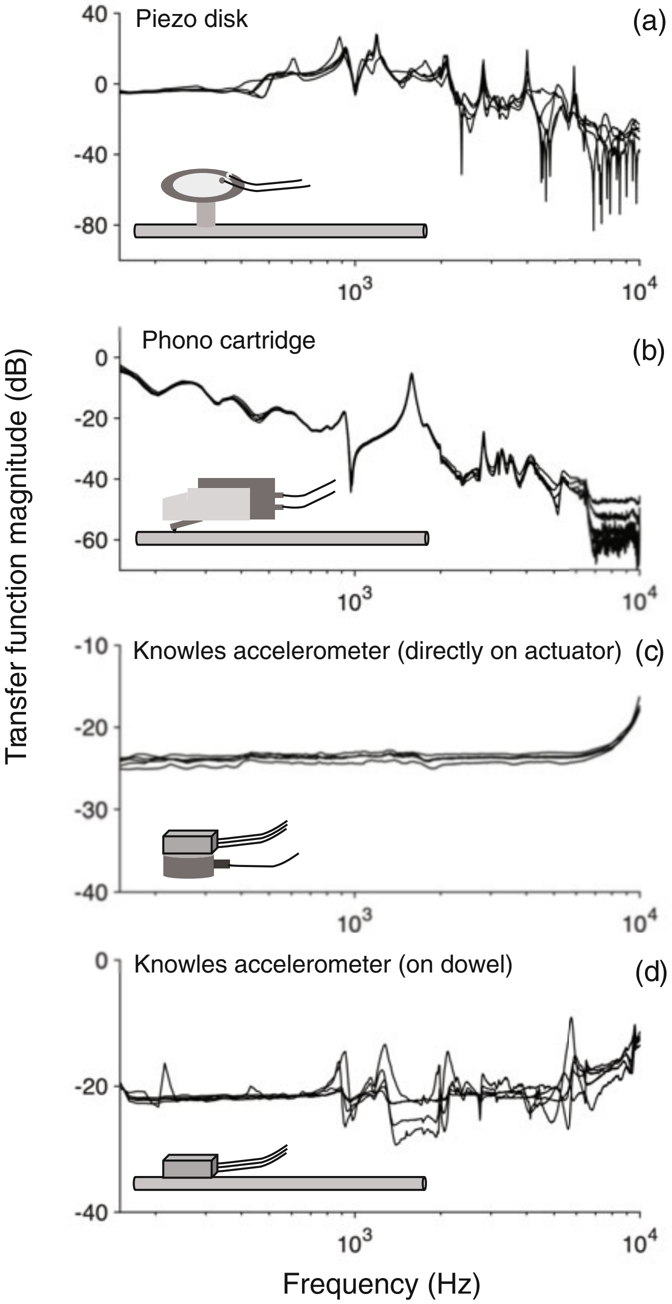
Our goal was to characterize the frequency response of the sensors over the range of 50–10,000 Hz and to assess the repeatability of their output. In particular, we wanted to capture variability in the sensors' frequency response across measurements, since the manner in which a sensor is attached will influence its frequency response, and this influence can be greater for non-standard sensors.

8.4.1 Vibration Sensors: Methods

We played back and recorded broadband noise (50–10,000 Hz) through a dowel (6.25 mm diameter) held in a PanaVise. We used a 9 mm × 3.2 mm LRA as a playback device and calculated the compensation filter using an accelerometer (Vibrametrics 9002A with P5000 Power supply, Mistras Group, Princeton Junction, NJ, USA; sensitivity is 100 mV/G and we used 10x gain) attached to the dowel 10 cm from the LRA. We attached each sensor in turn to the dowel opposite the accelerometer (Fig. 8.1c). We modified the piezo disk by gluing a short length of dowel (8 mm long × 6 mm diameter) to the center of the metal disk on the opposite side from the ceramic wafer; a consistent means of attaching a piezo disk to the substrate can improve the sensitivity and repeatability of the measurements (D Dunn, personal communication). We attached the piezo disk to the stem with wax. We positioned the phonograph cartridge by attaching it to a dowel held by a Panavise, such that the tip of the stylus lightly but firmly contacted the stem opposite the accelerometer. We tested the Knowles accelerometer as with the other sensors, attaching it with wax to the dowel. In addition, to assess the influence of attaching the sensor to a curved surface of the dowel rather than to a flat surface, we also conducted a second test of the dowel in which one surface of the Knowles was attached to the LRA and the other was attached to the Vibrametrics accelerometer. The piezoelectric disk and phono cartridge require a high-impedance input, provided by the audio interface (Behringer U-PHORIA UMC202HD audio interface, Behringer USA, Bothell, WA USA). The interface was connected to a Macintosh computer. The Knowles accelerometer was powered by a custom-made amplifier and power supply (circuit available from the authors on request).

To estimate the repeatability of the measurements from each sensor, after the first recording we detached the sensor, re-attached it in approximately the same location, and again recorded the played-back noise for a total of 5 sets of recordings per sensor. For each measurement, we obtained the transfer function between the signal acquired by the Vibrametrics accelerometer and the signal acquired by the sensor.

Fig. 8.6 Comparison of the frequency response of three vibration sensors, including (**a**) a piezo disk, (**b**) a ceramic phonograph cartridge, (**c**) a Knowles accelerometer attached directly to the flat surface of an actuator and (**d**) a Knowles accelerometer attached to the dowel



8.4.2 *Vibration Sensors: Results and Discussion*

The frequency responses of the piezoelectric disk and phonograph cartridge are complex and are not identical each time the sensor is attached to the substrate (Fig. 8.6a, b). The frequency response of the Knowles accelerometer (when attached to the surface of the LRA) is flat up to ~7000 Hz, after which the response is influenced by the resonant frequency of the sensor (Fig. 8.6c). However, after attaching this sensor to the dowel, its frequency response was more variable (Fig. 8.6d).

The complexity and the variability in the frequency response of these sensors between uses is a constraint on their utility for studies of vibration-mediated interactions. These issues with the frequency responses of the tested sensors have at least three causes. The first is that we have re-purposed the sensor for a new use, and phonograph cartridges provide an illustrative example. They are designed to reproduce the waveforms inscribed in the groove of a phonograph record; as the stylus travels through the groove, the downward pressure applied to the stylus is a constant, determined by the weight of the arm that holds it, and the waveform inscribed in the vinyl causes side-to-side movement of the stylus that is transferred to the piezoelectric element inside the cartridge. Placing the stylus in contact with a plant stem is a novel use of the sensor that does not provide the same kind of motion it was designed to detect, nor does the method used to hold the cartridge in place provide the repeatable pressure on the stylus that a phonograph player would.

The second cause of complexity and variability in frequency response is illustrated by piezoelectric disks. While these ubiquitous sensors have a range of uses, the metal disk to which the piezo element is attached has resonant peaks that vary with the size of the disk and the way it is attached to the substrate. The addition of a dowel to facilitate a more consistent point of attachment between the disk and the substrate did not in this case eliminate variability in measurements, especially at higher frequencies.

The third cause of a lack of repeatability in the sensors' frequency response is the manner in which we attached them to the substrate. Results from the Knowles accelerometer reveal that when this sensor is firmly secured to a flat surface each time it is used, it can provide a reliably flat frequency response. However, attaching it to a dowel introduced variability in frequency response from one use to the next. For studies where repeatable measurements are important, however, the unit can be glued onto the substrate (Cocroft 1999), which takes more time but provides a more secure coupling between sensor and substrate.

8.5 General Discussion

The measurements made here of the performance of various vibration playback and recording sensors illustrate a few general points. Here we discuss the opportunities provided by the devices we tested, as well as their limitations.

8.5.1 Inexpensive Playback Devices: Advantages and Limitations

The data presented in this chapter illustrate that a range of devices can produce playbacks that closely match the frequency spectrum of the original signal, as long as the user calculates a compensation filter, applies it to the stimuli, and calibrates the amplitude of the playback. Because the compensation filter adjusts the relative amplitude of different frequencies in the signal relative to each other, stimuli containing only a single frequency do not require a compensation filter, only amplitude calibration. Especially for playback experiments where higher throughput is required and which involve multiple channels (e.g., Appel and Cocroft 2014), there is a substantial cost savings from using actuators like the ones tested here, with no reduction in playback quality.

The main limitation of the piezoelectric actuators and LRAs tested here, relative to the shaker, is the total displacement possible. For the shaker, the maximum peak-to-peak displacement is 4 mm, while for the piezo actuator the maximum peak-to-peak displacement is 16 μm. We did not measure peak displacement for the LRA, but for the playback of caterpillar feeding vibrations the maximum peak-to-peak displacement (obtained by integrating the laser signal) was 8 μm. For the plant-borne vibrations of the feeding and signaling insects we have worked with, however, peak-to-peak displacements are small (on the order of 1–10 μm) and all of the devices we used can produce playbacks with that amplitude. For modified loudspeakers, millimeter-scale displacements are possible with larger speakers. So the limited peak-to-peak displacement of most of the actuators we tested is not a disadvantage for playback of relatively low-amplitude vibrations like the ones produced by insects on plants; and for playback of higher-amplitude vibrations, modified speakers of the appropriate size should be able to produce the needed displacement. The need for larger total displacement is most likely to arise when reproducing low-frequency signals produced by relatively large signalers.

An additional advantage of the LRAs for playback is that, for suitable structures such as woody stems, the actuator can be attached directly to the substrate. In contrast, for all of the other devices tested, the actuator must be supported on a flat tabletop (mini-shaker) or otherwise held in place (piezo actuator, modified speaker). The ability to attach an actuator directly to the substrate without external support is a distinct advantage in some circumstances, such as for conducting a playback at a particular location on a large woody hostplant. However, very light plant structures such as leaves, petioles, or the stems of small herbaceous plants cannot support the weight of an actuator, so an external positioning system is needed.

8.5.2 Inexpensive Vibration Sensors: Advantages and Limitations

The availability of sensitive, low-cost vibration sensors such as piezo disks overcomes some serious limitations of expensive, dedicated equipment such as laser vibrometers and calibrated accelerometers. Although lasers and calibrated accelerometers have been used in the field, lasers and most accelerometers are not weather-resistant, and the need to avoid damaging difficult-to-replace sensors limits the kind of work that can be done. In contrast, monitoring vibrational signals in natural environments is eminently feasible, as the sensors can be waterproofed for outdoor use and replaced as needed. Furthermore, their low cost makes them useful for applications requiring many sensors at a time, as long as quantitative characterization of the true frequency spectrum or amplitude is not needed. The only limiting factor is the number of channels of data acquisition. Sensors such as piezo disks are also very suitable for use in science outreach activities. Piezo disks can be waterproofed and mounted on a clip for easy attachment to vegetation, and the cable can be plugged into an amplified speaker for a very simple "vibrational prospecting" kit.

Additional work will be required to overcome the main limitations of inexpensive vibration sensors—i.e., their complex frequency response and the variability in output between repeated uses. If attachment methods can be developed that maximize the repeatability of the output of these sensors, then it would be possible to design a compensation filter to convert the output to closely match the output that would have been provided by a calibrated sensor. It is likely, however, that attachment methods that yield more repeatable measurements (such as using adhesive rather than wax) will require more advanced preparation, leading to a tradeoff between the quality and the ease of the measurement. And of course, the method of attachment to the substrate is a source of variation in output for any sensor, including the most expensive dedicated equipment.

Any of the sensors we tested here can be used to calibrate reliable playback experiments, under certain conditions (see Cocroft et al. 2014 for a more extended discussion of this point). One such condition would be if the original signal is recorded at the location where the playback subject will be, and the playback is calibrated on the same substrate without detaching the sensor. Another would be if the frequency range of the playback stimuli fell within a frequency range where the sensor does yield consistent measurements. A third would be if the sensor could be attached in the same manner between locations, as by adhesive contact of the entire sensor (in the case of a piezo disk or film) or by embedding the sensor within a medium such as soil. The second two conditions would need to be tested further to ensure that the measurements were indeed consistent.

For sensors then, our current information indicates that for experimental work with vibrations, it remains important to have at least one calibrated vibration sensor, such as an accelerometer. If a low-cost sensor can be identified that does provide consistent measurements from one use to the next, this would be extremely useful.

LRAs (which can also be used as sensors) offer some promise in this regard, though their output when used as sensors is low and their consistency from one measurement to the next has not been demonstrated. Lower-cost accelerometers, such as the Knowles accelerometer tested here, provide another potential solution, as long as their sensitivity, frequency range, and mass are appropriate for the questions addressed. However, these accelerometers are not individually calibrated and once they are attached to a cable, their sensitivity and resonant frequency can vary from one unit to the next, making it advisable to calibrate their output using a factory-calibrated sensor.

8.6 Conclusion

The availability of low-cost playback devices and vibration sensors provides new opportunities for the study of vibration-mediated interactions. For playback devices, inexpensive solutions are available that perform as well as expensive, dedicated devices. For sensors, the limitations of the devices we tested mean that for some research purposes, dedicated equipment such as individually calibrated accelerometers or laser vibrometers are necessary. At the same time, the availability of low-cost sensors opens up avenues for exploration in directions that the use of more delicate, less replaceable sensors does not support, and use of these sensors has the potential to advance the field in significant ways.

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