22 Acoustic Monitoring of Insects

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Farmers, grain elevator managers, and food processors often sample grain for insect-damaged kernels and numbers of live adult insects (Yigezu et al. 2010), but these easily obtained measurements of insect levels do not provide reliable estimates of the typically much larger populations of immature insects feeding internally (Perez-Mendoza et al. 2004). If stored products were transparent, sampling of this much larger immature population could enable better estimates of total population levels, earlier detection of internal insect infestations, and improved forecasting of when to aerate, fumigate, or sell for optimum profitability (Adam et al. 2010). Retail store managers could better focus on where and when to conduct sanitation efforts and remove infested stock or spillage (Arbogast et al. 2000). Breeders could screen more quickly for different varieties of grain that were resistant to larvae of different pest species (Devereau et al. 2003).

Used carefully, acoustic devices provide a measure of "transparency" and enhance inspection of many stored products that otherwise could not be monitored inexpensively without destructive sampling. In addition, acoustic methods can be adapted for automated, continuous monitoring, increasing the likelihood of detecting infestations before they cause economic damage. Such capability can be of benefit to pest managers, regulators, and researchers. New acoustic devices and signal processing methods have been developed in the last few years that greatly increase the reliability and efficacy of insect pest detection (Mankin et al. 2011, Leblanc et al. 2011).

Equipment

Microphones are ubiquitous in cell phones and recorders, particularly the inexpensive, compact electret microphones, but piezoelectric sensors that are in direct contact with the grain or stored product containing the insects are better choices for many stored product insect detection applications. Piezoelectric sensors reduce the losses caused by attenuation when acoustic signals cross from one transmission medium to another. Commercially available guitar pickups, geophones, and accelerometers (see Figure 1) contain piezoelectric sensors that use different kinds of amplifiers to increase signal amplitudes sufficiently for data analysis and interpretation. All of these sensors have been used successfully to detect insects in stored products. Table 1 lists many of the stored product insects that have been monitored by acoustic sensors of different types.

Because small insects, particularly young larvae, are weak emitters of sound, researchers have developed and tested various procedures to minimize or filter out interfering background and electrical noise. Electrical noise often can be reduced by placing amplifiers as close to the sensor as possible. Calibrated, low-noise amplifiers are typically the most costly part of a detection system, but when many sensors are employed in a detection project, the costs can be reduced by multiplexing many sensors to one amplifier. Several soundproofing and vibration-reduction methods have been described for sampling stored grain (Vick et al. 1988a, Hagstrum and Flinn 1993, Mankin et al. 1997b), and are applicable for detection of insects in packaged goods as well.

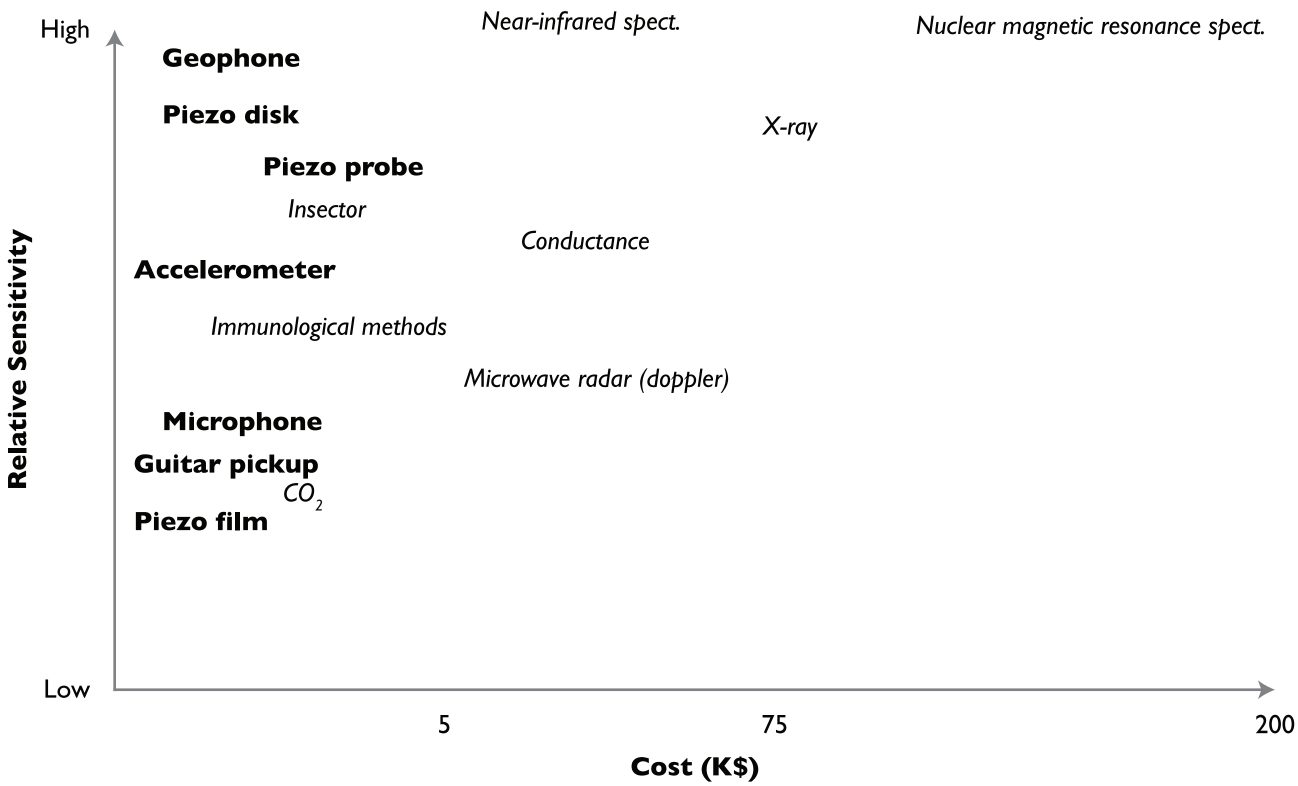

Figure 1. *Comparisons of the sensitivities and costs of different acoustic sensors (bold) in relation to other detection methods (italics): piezo film, probes, and disks, ultrasonic sensors, accelerometers, and geophones typically use piezoelectric technology, and cover a range from low to high sensitivities. Other detection methods, including CO_2 emission, immunological methods, the Insector (Flinn et al. 2006, Opit et al. 2009), microwave radar, X-ray, infrared spectroscopy, and nuclear magnetic resonance, can have high sensitivity relative to acoustic methods, but also may be considerably higher in cost (Chambers et al. 1984, Neethirajan et al. 2007, Pearson et al. 2007).*

Ultrasonic sensors that detect signals between 20 and 200 kHz can be useful for detecting nearby insects in moderate to high levels of background noise. The benefit is that background noise usually is low at ultrasonic frequencies. Unfortunately, the signals attenuate rapidly over short distances in stored grain (Shade et al. 1990). One solution to this problem in sampling stored grain is to place the sample inside a long, narrow metal cylinder so that no individual grain is more than 2 to 3 cm from the edge. This also enables the approximate location of each infested kernel to be identified, and the infestation density can then be estimated as the number of separate infested locations (Shuman et al. 1993, 1997).

When background noises cannot be filtered out entirely, it is possible to filter out frequencies above and below the peak energies of signals typically produced by the target insect. Modern amplifier systems often enable this capability, and much of the interference from background noise can be eliminated by filtering out signals below 200 Hz.

Insect Sound-Production Variability

Adult and immature stages of stored product insect pests vary considerably in size and in the amplitudes and rates of sounds they produce (Arnett 1968, Mankin et al. 1997a). Relatively large *Sitophilus oryzae* (L.) and *Tribolium castaneum* (Herbst) adults, for example, are more readily detected than intermediate-sized *Rhyzopertha dominica* (F.), while the smaller *Cryptolestes ferrugineus* (Stephens) and *Oryzaephilus surinamensis* L. are less readily detected (Hagstrum and Flinn 1993). Some insects become quiet when they are disturbed, and the time needed for them to return to normal activity after a disturbance must be taken into account when they are monitored (Arnett 1968, Mankin et al. 2011). The rate of sound production also is affected by external factors such as temperature and disturbance levels. Vick et al. (1988a) determined that *S. oryzae* larvae in grain can be detected from distances up to 10 to

15 cm. *Tribolium castaneum* adults were detected up to 18.5 cm (Hagstrum et al. 1991). On average the sound production rate of immature stored product insects tends to increase with instar, as was found for *S. oryzae* larvae in grain (Pittendrigh et al. 1997, Hickling et al. 2000) and *Callosobruchus maculatus* (F.) larvae in cowpeas, *Vigna unguiculata* (L.) Walp., (Shade et al. 1990). Also, externally moving adults often produce sounds at considerably higher rates than internally feeding larvae, up to 37 times higher for *R. dominica* (Hagstrum et al. 1990), and 80 times higher for *T. castaneum* (Hagstrum et al. 1991). It should be noted, however, that because sound levels attenuate with increasing distances from a sensor, a small larva in a nearby grain kernel might be detected at the same time that signals from a much larger adult outside the 15 to 20 cm active space might fall below background noise levels. In addition, a small adult insect like *C. ferrugineus* will move through the interstices between grains easily and produce fewer sounds than larger adults such as *R. dominica*.

Disturbance can enhance or reduce detectability of stored product insect pests, depending on the species, and increases in temperature usually result in increased rates of sound production until temperatures exceed 30 to 40°C. Stirring of grain containing 4th-instar *S. oryzae*, for example, reduced sound production for periods of up to 20 minutes (Mankin et al. 1999). Adult *T. castaneum* sound production increased between 10 and 40°C (Hagstrum and Flinn 1993), while *C. maculatus* larvae decreased their rates of sounds above 38°C in cowpeas (Shade et al. 1990). Sound production of *S. oryzae* adults in grain decreased above 30 to 35°C, and *R. dominica* adult sound production rates plateaued above 30°C (Hagstrum and Flinn 1993).

Rapid heating has been tested to increase the detectability of adults and internally feeding larvae in stored grain initially at low temperatures below 20 °C. The use of radiant or convective heat, to raise the temperature rapidly above 29°C, increased the rate of sounds from internally feeding *S. oryzae* larvae by a factor of 2 to 5 (Mankin et al. 1999). A patent was issued in France for heating grain to increase insect sound production (Mihaly 1973).

Under conditions of low disturbance and optimal temperatures, monitoring times of 180 seconds are adequate to reliably detect many stored product insects. The minimum monitoring interval depends on the fraction of time the insects are active. Vick et al. (1988b) found that *R. dominica* produce feeding sounds in grain in 61% of 5-minute intervals recorded over a 7-day period, *Sitotroga cerealella* (Olivier), 71%, and *S. oryzae*, 90%, and that quiescent periods occurred primarily during molting.

Acoustic Signatures and Temporal Patterns of Insect-Produced Signals

Problems in distinguishing sounds produced by target species from background noise and sounds from other insects have hindered usage of acoustic devices, but new devices and signal processing methods have greatly increased detection reliability. One new method considers spectral and temporal pattern features that prominently appear in insect sounds but not in background noise, and vice versa. Insect chewing and movement sounds usually have acoustic signatures (high-frequency components containing few harmonics) and they occur in bursts of short, 3 to 10 millisecond impulses (Potamitis et al. 2009, Mankin et al. 2010, Mankin and Moore 2010). Listeners or scouts can readily identify many distinguishing characteristics in the sounds produced by a target species after about an hour of training (Mankin and Moore 2010). Better understanding of these signal characteristics has led to improved capabilities for automated insect detection and monitoring (Mankin et al. 2010, 2011).

Efficacy and Reliability of Acoustic Detection Devices

The efficacy of acoustic devices depends on many factors, including sensor type and frequency range, substrate structure, interface between sensor and substrate, assessment duration, size and behavior of the insect, and the distance between the insects and the sensors. Larvae and/or adults of 18 species of stored product insect pests have been detected in grain or packaged goods using one or more of six types of acoustic sensors (Table 1). Considerable success has been achieved in protection against false positives (predicting the presence of a target insect when none is present) and some with false negatives (predicting the absence of insects when one is present) in detecting grain insect pests. For example,

Table 1. *Stored product insect pests of different stages detected with different types of acoustic sensor (Adapted from Mankin et al. 2011)*

Species (Order[a]: Family)	Stage[b]	Sensor[c]
Achroia grisella (F.) (Lepidoptera: Pyralidae)	L	p_u
Acanthoscelides obtectus (Say) (Bruchidae)	(A)	p
Alphitobius diaperinus (Panzer) (Tenebrionidae)	L, (A)	p
Anobium punctatum (DeGeer) (Anobiidae)	L	p
Callosobruchus chinensis (L.) (Bruchidae)	L	m
Callosobruchus maculatus (F.) (Bruchidae)	A, L	p, p_u
Cylas formicarius elegantulus (Summers) (Curculionidae)	L	m_c
Cryptolestes ferrugineus (Stephens) (Laemophoelidae)	A	p
Oryzaephilus surinamensis (L.) (Silvanidae)	A	p
Plodia interpunctella (Hübner) (Lepidoptera: Pyralidae)	L	p
Rhyzopertha dominica (F.) (Bostrichidae)	A, L	m_c, p
Sitophilus granarius (L.) (Curculionidae)	A, L	p
Sitophilus oryzae (L.) (Curculionidae)	A, L	m, m_c, m_e, p, p_f, p_u
Sitotroga cerealella (Olivier) (Lepidoptera: Gelechiidae)	L	m_c, p, p_u
Stegobium paniceum (L.) (Anobiidae)	A	m_e, p_f
Tribolium castaneum (Herbst) (Tenebrionidae)	A	m_e, p, p_f
Tribolium confusum Jacquelin du Val (Tenebrionidae)	A, L	p
Zabrotes subfasciatus (Boheman) (Bruchidae)	L	p_u

[a]Species Order is Coleoptera if not specified.
[b]A, adult; L, larva
[c]m = microphone (unknown type), m_c = capacitance (condenser) microphone, m_e = electret microphone, p = contact pickup using PZT (Lead zirconate titanate) piezoelectric transducer, p_f = PVDF piezoelectric film transducer, p_u = PZT ultrasonic transducer (20-200 kHz).

Shuman et al. (1993) found that 6% of grain samples infested with *S. oryzae* larvae were falsely rated positive for infestation and 34% were falsely negative. Adult *R. dominica* were identified successfully in continuous monitoring in 73% of tests, *T. confusum* 72%, *S. granarius* 63%, and *O. surinamensis* 61% (Schwab and Degoul 2005). Larvae were identified with somewhat less success (73% for *S. granarius*, 58% for *S. cerealella*, 57% for *R. dominica,* and 52% for *T. confusum*).

In grain stored in on-farm (65 to 191 metric ton) bins, an insect detection threshold of approximately eight intervals per day with sounds resulted in 11.5% false positives, 15 to 40% false negatives for more heavily infested bins and 52 to 86% false negatives for some of the more lightly infested bins (Hagstrum et al. 1996). The false positives are most often caused by electrical noise because grain is a good sound insulator. The false negatives are probably the result of insects being inactive when a sensor is checked, thus the number of false negatives may be reduced by checking a sensor more often.

Successful Applications of Acoustic Technology for Stored Product Pest Detection

Acoustic methods have been applied successfully for grain inspection (Vick et al. 1988a, b, Pittendrigh et al. 1997, Shuman et al. 1993, 1997), estimations of population density (Hagstrum et al. 1988, 1990, 1991, 1996), and mappings of stored product insect pest distributions (Hagstrum et al. 1996). Data collected by acoustic sensors from grain infested with a single species and stage typically provides sampling statistics similar to those estimated from grain samples for *R. dominica* larvae (Hagstrum et al. 1988) and *T. castaneum* adults (Hagstrum et al. 1991).

Acoustic devices of various kinds have been marketed for field use, and instrumented sample containers in sound-insulated chambers have been developed for commodity inspection. A sample container in a sound insulated chamber has been marketed for laboratory use (Sito Detect, Fleurat-Lessard 1988). Other sample containers with acoustic sensors (Pest-bin detector and EWDLab, Systelia Technologies, Carqueiranne, France) are discussed by Mankin et al. (2011). Probes for field use may be pushed directly into a commodity, i.e., Larva Sound Detector (Bad Vibel, Germany, Weinard 1998) and EWD Portable (Gobernado et al. 2005, Schwab and Degoul 2005, Fleurat-Lessard et al. 2006) or may be attached to a waveguide that is inserted into the substrate or commodity, e.g., the Pest probe detector (Sound Technologies, Alva OK, Betts 1991).

Another successful acoustic detection device, reported by Kennedy and Devereau (1994), was a microphone system that monitored insect population levels in bag stacks in Zimbabwe. An automated system combining microphones, light-emitting diodes, and vibration sensors successfully distinguished *S. oryzae* from *T. castaneum* and *Stegobium paniceum* (L.) (Mankin et al. 2010).

Continuous monitoring with automated acoustic systems has considerable potential for enabling early detection of small populations of stored product pests. For example, Hagstrum et al. (1996) found that automatic continuous monitoring detected insects in grain bins 3 to 28 days earlier than taking grain samples. Insect infestation levels were estimated from the number of 10-second intervals with insect sounds over a range of 0 to 17 insects per kilogram. Automatic continuous monitoring with sensors in grain is advantageous partly because adult grain pests often are very mobile, and many will eventually move close enough to a sensor to be detected. In the on-farm grain bin study of Hagstrum et al. (1996), insects initially were most abundant in the top center of the grain bin. Subsequently, they dispersed in all directions and were found at 16 additional locations after 85 days of storage. This dispersal might improve overwinter survival because grain at locations deeper in the grain mass will remain warm longer.

Finally, networking opportunities provided by modern communication systems could assist in agricultural sourcing and tracing initiatives (Elliot et al. 1998) and permit tracking of insect infestations in grain and other commodities as they move through the marketing system. The capability of acoustic sensor systems to interface directly with intelligent computer networks enables reductions in the labor costs and risks of collecting such information. As reliability and ease of use increase and costs decrease, acoustic devices have considerable future promise as insect detection and monitoring tools.

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S156 – 22 December 2011