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Recent advances in exploration of acoustic pest management: A review

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Abstract
The need to find more efficient and non-hazardous environment friendly pest management strategies have paved the way to the discovery of a wide range of innovative approaches in pest management. Keeping up with the latest trends in agriculture, acoustic technology can be considered a viable option for pest population management. Acoustic is the scientific study of how sounds are created and transmitted to the receiver. Since early 1900s, this technology has been applied to detect, identify and monitor some of the pest species in various countries. Acoustic methods have been widely explored either to trap/detect the insect pests or to manipulate the behavior by interrupting interspecific communication. Common acoustic devices used in pest management are microphones, ultrasonic transducer, laser doppler vibrometer and some sensors like accelerometers, piezoelectric disks and acoustic probe etc. Management of insect pests through acoustic devices has gained momentum due to their eco-friendly nature and hence the technology becomes as an ideal component of both IPM and precision farming. Although acoustics has been recognized as a highly efficient eco-friendly method of pest management, the widespread adoption of the technology has been hindered due to their relatively high cost as well as requirement of high expertise in the field. Exploration of advanced technologies in the development of more reliable and cost effective acoustic devices and their further improvement for easy handling may pave the way for their wide applicability in true sense.

Keywords: Acoustic, ultrasonic transducer, accelerometers, piezoelectric disks, acoustic probe, pest management

Introduction
Since early 1900s, acoustic has been used in pest management programme to detect and monitor some of the pest species in various countries. Acoustic recording and playback technologies have been employed for insect detection and monitoring successfully over the years [1] and this process has only been hastened with the development of modern technology and science. With the recent advancement in agricultural science, the study of acoustic behaviour has developed into one of the prominent areas of insect ethology [2]. According to the Acoustical Society of America, acoustic is defined as "(a) Science of sound, including its production, transmission, and effects, including biological and psychological effects (b) those qualities of a room that together determine its character with respect to auditory effects". The branch of acoustics associated with living organisms including insects is known as bioacoustics. In terms of agriculture, acoustic studies have mainly been conducted to attract and trap insects for pest population surveys/monitoring [3], sterilization/killing & biological studies [4,5] and to manipulate insect behavior or interrupt intraspecific communication using either sound [6] or vibrational signals transmitted within the host plants [7].

Communication in insects
Acoustics in case of pests including insects, other arthropods and vertebrates is based on the frequency range of the target pests. In comparison to the hearing range of human beings, which falls between 20 Hz-20 kHz, insects such as mosquitoes possess a hearing range of 38-44 kHz while rodents have the hearing range of 60-72 kHz [8]. The frequencies of hearing above 20 kHz is considered as ultrasound while that of below 20 Hz is considered as infrasound [9]. So the communication of insects usually consists of sound, ultrasound, infrasound as well as vibrations. On the basis of the medium, communication in insects can be

classified as air borne sounds (found in insects like cicadas and grasshoppers, which can be usually heard by humans) and surface borne vibrations (detected in treehoppers and termites). Both the mediums are utilized by the insects for communication for the purpose of courtship, as an alarm signal in response to threat and danger, as a part of defensive behavior and marching in groups. In case of social insects, it is used for communication which is necessary for various social interactions [10].

Use of acoustics in agriculture

General awareness about the risks of exposure to chemical methods of pest management on human health and environment has jumpstarted the effort to look for alternate non-chemical methods of pest management [11]. Alternate methods of pest management are increasingly being perused given their more eco-friendly and sustainable nature. Most of the non-chemical methods for pest management involve manipulation of the target organisms behavior using different external stimuli [12]. The non-chemical alternatives present today require a manual approach, which is time consuming, labour intensive and error-prone [13]. Acoustic sensing is one of the main branches of automatic detection and identification. It is an eco-friendly approach without any side effects to the environment or non-target organism and also possesses the ability to detect pests in soil, stored grain or wood [14]. Acoustic devices usually work in a frequency bandwidth inaudible to humans and thus cause no disturbances. The insect pests can be detected and managed without causing any harm or loss to the substrate.

Acoustic methods

The maiden report of using of acoustic methods in pest management was successfully demonstrated by Kahn and Offenhauser [15] in 1949 by using loudspeakers to attract and capture the male *Anopheles albimanus.* Eventually acoustic devices were applied in field and laboratory studies to trap other mosquitoes [16], Chironomid midges [17, 18] and *Scapteriscus* spp. [19]. Acoustic sensors used in recent studies include accelerometers, piezoelectric sensors, microphones and ultrasonic transducers which have been used to detect and identify insects. Laser doppler vibrometer is the latest sensor which is extremely useful for insect detection and identification.

1. Accelerometers

The accelerometer is an acoustic sensor which measures the acceleration forces in its surrounding by sensing the vibration or impact. It is a microchip like device which is clamped gently but firmly to the stem or the stalk of the plant. The signals detected by the accelerator are transmitted as output signals to a wireless computer for further assessment. It is usually used to detect larvae or adults of pest species. The most advanced and preferred model is that of a Micro Electric Magnetic System (MEMS) accelerator. The working principle of the MEMS is based on the presence of a suspended mass between two capacitive plates, which when faced with the application of a force creates a small voltage of electricity which is sent out as an output signal. An acoustic system was developed [20] which included an accelerometer, a charge amplifier, and a digital audio tape recorder. This device was used to detect termite infestations in urban trees. The accelerometer was attached magnetically to a 30 cm spike or an 8-15 cm screw inserted at the recording site. A 180 second period was recorded and monitored with headphones in each site with the recorded signals digitized and analyzed with a digital signal processing system that provided computer assessment of activity and also distinguished termite sounds from background noise. To avoid the damage caused due to clamping of accelerometer, an improved technique was devised [21] which could safely attach an accelerometer to wheat stems. The accelerometer was used to detect larvae of *C. cinctus* and *Metamasius callizona* inside wheat stems without causing injury to the plants. The system was able to distinguish the vibration produced by small larvae (0.3-0.8 g) from that produced by larger insects (30-40 g). Two portable acoustic devices i.e., an accelerometer connected to a charge amplifier and a sensor-preamplifier module connected to an amplifier unit were used to detect two species of subterranean vibrations of root feeding white grubs in Australia [22]. Computer analysis enabled the identification of the distinctive sounds produced by *Dermolepida albohirtum* and *Antitrogus* spp. and also distinguished them from sounds of non-damaging white grubs. Mankin and Moore (2010) [23] gathered signals with the help of accelerometers attached to charged amplifiers to detect adult and larval *Oryctes rhinoceros* in live and dead palm trees and logs in recently invaded areas of Guam, along with *Nasutitermes luzonicus* and other small, sound-producing invertebrates. The amplified signals were saved on a dual-channel, digital audio recorder sampling at 44.1 kHz (24 bits). In recordings at a survey location, the accelerometers were attached magnetically to 30 cm long spikes, inserted into the wood a few minutes before recording. Martin *et al*. (2013) [24] showed that the accelerometer had the potential to detect the larvae, adult and cocoon of *Rhynchophorus ferrugineus* in palm trees.

2. Piezoelectric sensors

It is a sensor which works on the principle of piezoelectricity. The piezoelectric disk generates a voltage when deformed. Some crystals like quartz have the ability to let electricity flow through them. When exposed to external force, the crystal gets deformed and the negative and positive charges inside the crystal get displaced leading to the formation of an electric voltage which helps in the detection of the pest. The core of a piezoelectric sensor is composed of piezoelectric crystals which are direct converters of mechanical stress to electric charge. A piezoelectric sensor was used to detect larvae of *Anoplophora glabripennis* in wood [25]. The sensor was mounted on a steel waveguide which was inserted into the wood to record vibration created by insects. A new impulse pattern was adopted called burst which could identify larvae at different ages in the cambium of sapwood and heartwood more accurately than automated spectral analyses. In 3-min recordings from infested trees, these impulse patterns featured 7–49 impulses separated by small intervals. A piezoelectric sensor was also able to detect *R. ferrugineus* activities inside palm trees by adopted speech recognition methodology which had an average detection ratio of 98% [26]. A light weight and user friendly version of this sensor was developed by Siriwardena *et al*. (2010) [27] by sandwiching the piezoelectric transducer together with two circular stainless steel discs of 4 cm diameter. One side of the disc was welded with a 1 cm long pin and the other side with a ring. The sensor was moulded using locally available material. The sensor was then mounted on the palm by pressing the needle of the sensor on each position. Additionally, the device possessed an electronic unit that processed the acquired sounds and a set of headphones to receive the output sound by the listener. The infested palms were detected with over 97% accuracy. Piezoelectric sensor was used to record substrate borne vibrational signals (SBVSs) of two prevalent pests, *Euschistus servus* and *Nezara viridula* [28]. Recordings were made by attaching the device to the plant by alligator clips at 55 cm above the soil. The recordings were then amplified and digitized using a speech analyses system. Gaussian mixture model (GMM) and probabilistic neural network (PNN) was used to distinguish the SBVs of different species. The detection and identification of the two insects was 83.2% and 71.5% accurate using PNN and GMM respectively. For the detection of adult beetles inside the grains, an acoustic detector system consisting of a 14-cm-long piezoelectric sensor mounted on the end of a probe that was pushed into the grain and a portable acoustic emission amplifier connected to a computer [29]. The system was very accurate (72–100%) in detecting 1 or 2 insects per kilogram of hard wheat grain. Mankin *et al*. (2016) [30] assessed the acoustic detectability of *R. ferrugineus* in Saudi Arabian date palm orchards by signal analyses which was developed to detect *R. ferrugineus* and another insect pest, *Oryctes elegans*, frequently co-occurring in the orchards, and discriminate them from each other as well as from the background noise. A titanium drill bit of 1.59 mm diameter was inserted near a site where infestation was suspected on the lower part of the tree or offshoot, along with a 1.9 cm diameter metal ferrule clamped to the bit to widen its base. A sensor-preamplifier module was attached to the ferrule with a high force magnet. The signals were fed from the sensor module through an amplifier to a digital audio recorder at a digitization rate of 44.1 kHz.

3. Acoustic probe

Acoustic sensors like accelerometer and piezoelectric sensors are integrated to form an acoustic probe. It is usually inserted into the area of the sound field to be studied *viz*. soil, stored grain or wood. A hand held instrument comprising of a special probe with a sensor designed to detect acoustic emissions produced by hidden insects known as an SP-1 probe, was manufactured by Acoustic Emission Consulting (AEC) to detect red palm weevil larvae in date palm trees [31]. However the device was flawed as it required a portable PC which had to be carried in the field for data acquisition and thus was practically impossible to use in large fields. Fleurat-Lessard *et al*. (2006) [32] constructed an acoustic probe called early warning detector. It was a 1400 mm length portable probe of built up with three levels acoustical sensors coupled to a computer-assisted processing system. The portable probe was inserted into bulk grain and the sound signals of the major grain insects were stored in a referenced database. A classification algorithm was developed for automatic recognition of the recorded signals. The adult *Sitophilus* were identified with an accuracy of 95.0% within a range of 200 mm. Some commercial acoustic probes available are the AED2000, a user-oriented acoustic probe sensor which was designed to meet the needs of a variety of industrial applications including pest detection and LAAR WD 60 Pro CSC which has been specially designed to detect *R. ferrugineus* in palms.

4. Microphone

It is a type of acoustic device which uses IA (Impact Acoustic measurement) as a technique of evaluating quality of agricultural produce. It helps in detection of insect, scab and sprout damage in kernels of grains. It is a non-destructive, economical alternative on the face of labour intensive, slow and expensive manual methods. The activity patterns of *Phyllophaga crinite*, *Phyllophaga congrua*, *Phyllophaga crassissima* and *Cyclocephala lurida* grubs were monitored with the help of electric microphones placed inside modified 4.5 cm stethoscope heads in small pots of bluegrass, *Poa arachnifera* [33]. Soroker *et al*. (2004) [34] employed an acoustic device (Larva Lausher, NIR, BadVilbel, Germany) to amplify red palm weevil larval activity inside tree trunks. In an experiment, IA signals were used to detect the extent of insect damage in wheat kernels. The bulk kernels were arranged into a single file stream by a vibration feeder and dropped on an impact plate made of polished stainless steel from a distance of 40 cm [35]. The audible and ultrasonic acoustic emissions produced from the impact of the wheat kernels with the steel plate were recorded using two microphones, sensitive to frequencies up to 100 kHz, each placed at a distance of 25 mm from the point of impact. The signals were digitized using a sound card and data acquisition triggered using an optical sensor. About 87% of the insect damaged kernels and 98% of the undamaged kernels were correctly classified. Two cardiods and one hypercardiod (AKG CK 91, Neumann KM 184, and Shure Beta 58A) microphones to classify the undamaged and damaged rice kernels [36]. The study showed that the distance of the microphones, the drop heights of samples and the material of plates for impact are critical. Also, both types of kernels had distinct frequency signatures. Validation experiments in the laboratory produced 93.3, 91.1 and 88.9 % recognition accuracy for the three microphones, respectively.

5. Ultrasonic transducer

The working principle of an ultrasonic transducer is such that when an electrical pulse of high voltage is applied to the ultrasonic transducer, it vibrates across a specific spectrum of frequencies and generates a burst of sound waves. Whenever any obstacle comes ahead of the ultrasonic sensor the sound waves will reflect back in the form of echo and generates an electric pulse. It is also known as an Ultrasound sensor. Fleming *et al*. (2005) [37] placed a pair of noncontact transducers acting as the emitter and the receiver on either side of two wood samples, 1 inch thick samples of aspen (*Populus* spp.) and red pine (*Pinus resinosa*) with and without cerambycid larvae. The wood was then scanned with 200 kHz ultrasound waves above wood fiber saturation and at low moisture conditions. The resulting transmission data were used to produce ultrasonic images with a state of the art, signal analyzer system for nondestructive sensing applications. Although detailed c-scan images were generated for all wood samples, regardless of species and wood moisture condition along with artificially drilled holes in the wood samples, the technology used was not considered feasible. A technology was demonstrated which used time of flight of ultrasound to improve the accuracy of insect damage detection in wood [38]. Five disks of *Robinia pseudoacacia* measuring 200 mm in diameter and 30 mm in thickness were used as specimens. The transducers were attached to both ends of each disk to produce and collect ultrasonic signals. Ultrasonic CT images of wood were reconstructed by ascertaining the transmission path of an ultrasonic wave in a cross-section of wood. The report showed that holes bigger than 13 mm diameter could be detected by the time of flight of ultrasound in the wood. A method called ultrasonic spectrum attenuation analysis was proposed to detect pest infestation in wood [39]. A wave travelling through wood can be attenuated by absorption or scattering. Two piezoelectric transducers (with 54-106 kHz bandwith) were positioned at opposite sides of a sample of wood from *Pinus densiflora* with a diameter of 96 mm to generate and receive ultrasound. Labview software was selected for ultrasonic spectrum attenuation analysis. Internal drill holes with a diameter of 3 mm could be detected under very severely varied contact pressure. The results showed that the spectral analysis has a high possibility in detection of internal insect than other conventional methods like time of flight based techniques. Ultrasonic transducers can also be used to emit ultrasonic waves as in case of commercial repellers and deterrents such as CLEANRTH Ultrasonic Bird Repeller, Ultrason X Ultrasonic Bird Control Device and BEATUNES Ultrasonic Animal Pest Repeller for invertebrate pests and other similar devices to repel rodents monkeys and other mammals like cats, dogs, skunks and squirrels.

6. Laser doppler vibrometer (LDV)

The principle of LDV is based on optical interference. It has broad frequency range and longer working distance of several meters. The laser beam from an LDV is directed at the surface of interest and the vibration amplitude and frequency are extracted from the doppler shift of the reflected laser beam [40]. It is used to measure non-contact vibrations of a surface. In comparison to other contact methods of measuring vibration, LDV offers an advantage as it can actively avoid the interference between sensors and specimens. A vibration sensor was developed that could classify the flying insect species using their wing-beat frequency as feature [41]. The sensor made up of a laser source and a phototransistor connected to an amplifying and filtering electronics board was used as a laser beam to measure wing beat frequency of flying insects. During flight, when the wings of the insect came across the laser beam, it led to partial occlusion of light which caused small light fluctuations. These fluctuations were captured by the phototransistor. As a result, the sensor was able to identify a beneficial species *Bombus impatiens* and two harmful mosquito species *Aedes aegypti* and *Culex quinquefasciatus* with 70.69-91.3% accuracy. Zorovic and Cokl (2015) [42] illustrated a method using a portable LDV to specifically detect infestation of *A. glabripennis* in four logs of *Populus* tree. A modified insect trap was used [43] by transforming it into an electronic monitoring device by installing an array of photoreceptors coupled to an infrared emitter, guarding the entrance of the trap. The beating wings of the insects flying in the trap intercepted the light and the fluctuation of light was recorded. Counts from the trap were then transmitted through a mobile communication network. The trap was able to distinguish *Bactrocera oleae* from *Lonchaea aristella* using the support vector machine (SVM) classifier with an accuracy of 76% was achieved. Two LDVs were used to record the vibrations transmitted along the plant during an attempt at mating disruption of the grapevine pest *Scaphoideus titanus* [44]. Moreover, acoustic devices like speakers, microcontrollers and amplifiers are often used as accessory devices to assist the above described devices.

Advantages

Insects usually communicate through ultrasonic and vibrational communication so their acoustic sensory systems can be manipulated to provide new ways of controlling the insect pest population. Although there is no dearth of efficient pest management strategies in the current agriculture scenario, side effects of chemo centric approaches to environment and non-target organisms is a huge cause of concern. Acoustic devices work on the principle of sound and vibrations and are both non-destructive as well as eco-friendly. Since acoustic devices usually work in a frequency bandwidth which is inaudible to humans, they cause no disturbances. Acoustic devices also enable the detection of specific stages of insect pests. Often the presence of pest becomes visible only at later stages of infestations. Acoustic technology can be used to successfully detect and manage these pests before the signs of infestation itself. Acoustic devices like accelerometers and piezoelectric sensors are known to interface well in soil and wood substrates while microphones are considered as being ideal for the detection of storage grains pests as well as in checking the quality of grain kernels. A major shortcoming of a majority of acoustic sensors is their inability to distinguish background noise as well as internal sounds within the tree or plant itself which interferes with the precise identification of insect signals. However, acoustic devices such as optical vibration sensors have been able to overcome this disadvantage**.** Acoustic devices such as the laser doppler vibrometer have broad frequency range and longer working distance upto several meters. The most advantageous feature of ultrasonic based devices is their ability to detect target pests without damaging the substrate.

Conclusion

Acoustic devices have been proven to be quite efficient in capture, identification, detection and behavioral manipulation of insect pest species. Although acoustic devices have been in use since the 1900s, the application of acoustic devices in pest management remains limited and mostly unexplored, especially in field conditions. The lack of exploration of acoustic technology in pest management can be attributed mainly to the fact that they are very expensive as compared to other available alternatives. The advancement in technology however ensures development of devices that are more affordable as well as easy to use. Also, modern technology has the potential to enhance the efficiency and effectiveness of these devices. It has been widely accepted that certain aspects of insect communication remain undiscovered and with it the possibility of a plethora of beneficial uses of acoustics in pest management are waiting to be explored. Considering all facts, acoustics methods as an eco-friendly and effective tool of IPM strategies to manage various notorious vertebrate pests, avian pests, forest, soil dwelling and other stored grain insect pests need to be explored.

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