Noise Shielding of Acoustic Devices for Insect Detection

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ABSTRACT The need to monitor hidden insects and automate the acquisition of data for grain management has led to development of electronic sound detection devices. Typically, insect feeding and movement sounds are low in intensity, and they attenuate rapidly in grain. The mean sound pressure level (SPL) generated by rice weevil, *Sitophilus oryzae* (L.) (Coleoptera: Curculionidae), larvae in wheat kernels is only 23 dB (referenced to 20 μPa) as measured by a microphone immersed in a grain sample 3 cm from a larva-infested kernel. Unless the noise background is reduced below these levels by 10 dB or more, an insect cannot be detected reliably. To establish guidelines and procedures for shielding acoustic detectors in a grain elevator or other noisy environment, a multilayered enclosure was constructed that attenuates sound by 70–85 dB between 1 and 10 kHz. This level of noise reduction is sufficient to enable detection of internally feeding larvae in grain samples at inspection facilities at commercial grain elevators, which have 50–80 dB SPL noise backgrounds between 0.1 and 10 kHz.

KEY WORDS stored products, sound, rice weevil

INSECTS HIDDEN inside fruit or kernels of grain can be detected acoustically by amplification and filtering of their movement and feeding sounds. Various systems have been developed to detect levels of infestation or monitor feeding activity over long periods. Recently described systems include the insect activity monitoring systems of Hagstrum et al. (1991, 1996), Webb et al. (1988), and Zakladnoi and Ratanova (1986), the acoustic location fixing insect detector of Shuman et al. (1993) and Hagstrum and Shuman (1995), the multiple acoustic sensor system of Hickling et al. (1994), the acoustic emissions detector of Fujii et al. (1990) and Sheffrahn et al. (1993), and the biomonitor of Shade et al. (1990). A major impetus for these applications of acoustic technology is the difficulty of detection by other techniques. A 2nd, practical impetus is the potential for automating the acquisition of information needed by grain managers (Hagstrum and Flinn 1993, Harein and Meronuck 1995) and regulatory agencies (Giler and Eustrum 1995).

Background noise presents a challenge to the practical use of acoustic insect detection systems on site in grain storage and management facilities. Even in a research laboratory, care must be taken to shield acoustic detection systems from external noises or to place the microphone near the insect producing the sound (Ewing and Bennet-Clark 1968, Ryker 1988). The initial studies to detect insects in stored grain were conducted in low-noise rooms (Adams et al. 1953, Wojcik 1968) or anechoic chambers (Vick et al. 1988b, Webb et al. 1988). Shade et al. (1990) reduced the need for audioband shielding by placing infested grains directly on a sensor and analyzing the ultrasonic portion of the signal. The attenuation coefficient of air increases by a factor of 1,000 between 500 Hz and 120 kHz (0.008 dB m^{-1} at 500 Hz [Beranek 1988a, where decibel is calculated as 20 $\log_{10}(P/P_{ref})$, P is the sound pressure, and P_{ref} is a reference sound pressure—in this case, the pressure 1 m closer to the source]) versus 7 dB m^{-1} at 120 kHz (Lawrence and Simmons 1982). Thus, the air itself is a good acoustic shield for ultrasonic background noise. The high attenuation coefficient, however, also reduces the distance from which a signal of interest can be detected. Ultrasound is less attenuated in wood, and Sheffrahn et al. (1993) reduced the number of "false positives" from background noise in a termite-infested wood sample by attaching a sensor to a reference (uninfested) sample and filtering out signals that occurred simultaneously in both wood samples. To develop a practical noise reduction system for long-distance monitoring of insects infesting grain, Vick et al.(1988a) constructed a small sound-insulated room from wood, foam, and sound board. Inside the insulated room, the noise background was reduced from 67 dB *ref*: 20 μPa sound pressure level (SPL) (that is, dB calculated with $P_{ref} = 20$ μPa, the threshold of human hearing [Beranek 1988a]) to 13 dB SPL. Although grain has a high attenuation coefficient compared with air (2 dB m^{-1} for grain at 0.5 kHz and 6 dB m^{-1} at 3 kHz, Hickling and Wei 1995), the sounds of larvae feeding in a grain sample could be detected from a distance of several centimeters at these noise background levels. Hagstrum and

Flinn (1993) constructed a chamber (35 by 40 cm) from a 1.9-cm thickness of plywood, foam, and sound barrier that reduced laboratory noise sufficiently to detect individual adult stored-grain beetles in 1-kg wheat samples. Such studies showed that a box constructed of wood, foam, and sound barrier provides good protection in a quiet laboratory, but the amount of shielding needed in a commercial grain elevator environment remains unknown.

From an acoustic perspective, the problem of shielding an insect detection device from background noise in a grain processing facility is primarily one of signal-to-noise ratio. The minimum shielding requirement for an acoustic sensor depends on the relative difference between the insect-produced signal and the noise background over the frequency range in which the sensor reliably detects a signal. The shielding ability of an enclosure at a given frequency depends on the intrinsic acoustic impedance of each insulating layer, the mismatch of impedances across layers, and on constructive and destructive interferences at layer boundaries (e.g., Beranek 1988b, Carn and Hoover 1988, Harris 1994).

Our article presents the results of studies designed to measure the levels of sound produced by larvae feeding internally in grain, determine the typical background noise levels at commercial grain elevators, and construct an insulated enclosure that reduces the background noise below the level of insect-produced sound. The insects were 4th-instar rice weevil, *Sitophilus oryzae* (L.) (Coleoptera: Curculionidae). The background noise measurements were made at Grain Inspection Service, Packers, and Stockyard Administration (GISPSA) (formerly Federal Grain Inspection Service) grain elevator offices near New Orleans, LA. The enclosure was constructed from multiple layers of absorptive materials, transmission barriers, and air gap, adapted from designs in Emme (1970), Kurze (1974), Crocker (1975), and Lord et al. (1980).

Materials and Methods

Muffle Box Construction. An 81-kg, 26-cm-thick, 6-layer muffle box was constructed (Fig. 1) based on a review of published transmission-loss characteristics of composite materials (Lord et al. 1980). The box (61 by 66 by 117 cm) had outer and inner frames of plywood. Loaded-vinyl transmission barrier (Illbruck, Minneapolis, MN) was glued to the interior surfaces of the plywood. A sheet of Illbruck Prospec, open-cell polyurethane acoustic foam (32.1 kg/m^3) was sandwiched between the 2 sheets of vinyl barrier. The 4 plywood sheets forming the inner frame were lined with removable Illbruck Sonex foam wedges (15.2 cm long) to reduce internal reflections of sound. The top was joined to the base with bolts and wingnuts, and four 7.6-cm rubber casters were attached

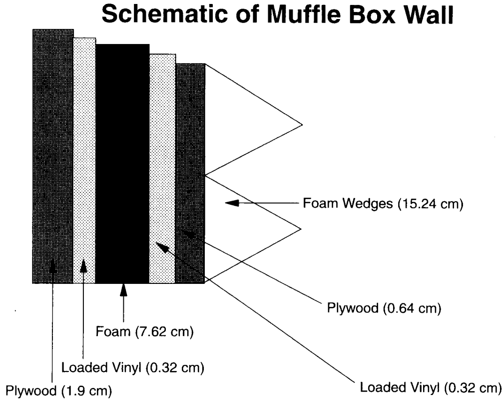

Fig. 1. Schematic of muffle box showing placement and dimensions of insulation layers.

to the base. To explore the possibility of reducing the muffle box dimensions, some of the measurements were done without an innermost layer of acoustic foam wedges (15 cm thick).

Noise-Reduction Measurements. Attenuation of the muffle box was measured in an anechoic chamber between 0.2 and 10 kHz. Sine waves were produced by a sweep generator (Wavetek model 185, San Diego, CA) and a 200-W power amplifier (Audiosource model AMP One, Burlingame, CA) connected to a speaker (JBL model Pro-III, Northridge, CA) set near the center of the chamber, 1.5 m from the box. The tones were detected by microphones inside and outside the box, equidistant from the speaker. The inside microphone (Brüel and Kjær [B&K] model 4145, Nærum, Denmark) was connected through a B&K Model 2639 preamplifier to a B&K Model 2610 measuring amplifier calibrated in dB *ref:* 20 μPa SPL The signals were bandpass filtered between 0.2 and 15 kHz (Krohn-Hite model 3100, Avon, MA). The amplifier output fed one channel of a digital tape recorder (Panasonic model SV-255, Matsushita Electric, New York, NY). A 2nd channel recorded the output of a portable microphone (Sennheiser model MKH 4161, Old Lyme, CT) suspended 30 cm from the muffle box. The 2 microphones have the same sensitivity between 0.2 and 15 kHz (50 mV/Pa), but the Sennheiser is more portable for grain elevator measurements. The gain of the power amplifier was adjusted so that the signal was at least 90 dB SPL, and the attenuation of the muffle box was calculated as the difference between the levels measured at the outside and inside microphones.

A 2nd method of measuring SPL that also measured the spectral characteristics of the grain-elevator background noise was to process the signal digitally (Mankin 1994). Recorded signals were conditioned with a 12-kHz lowpass antialiasing filter and then digitized at 25 kHz by a 12-bit MetraByte (Keithley/MetraByte, Taunton, MA) DAS-16G A/D board installed in a 80486 microcomputer. Spectrum periodograms (mean power spectra averaged over short intervals) were constructed by techniques described in Embree and Kimbell (1991) using DAVIS, a custom-written signal processing and spectral analysis computer program (Mankin 1994). Unless otherwise stated, no analog filtering was done on signals processed digitally, except by the 12-kHz antialiasing filter, and periodograms were generated from 10-s means by averaging 4096-point spectra over consecutive 10-ms increments. The amplitude of a periodogram at a given frequency is specified as a spectrum level, a measure of SPL adjusted for the bandwidth = SPL − 10 $\log_{10}$[frequency bandwidth] dB (Beranek 1988a). In the periodogram, the bandwidth is 1 Hz, centered at the specified (reference) frequency. Spectrum levels were calibrated by reference to SPLs measured with the B&K Model 2610 amplifier. Both individual and multiple tones were included in the calibration.

The noise produced by a portable sieve shaker (Combustion Engineering model RX-24, Gastonia, NC) provided a simulation of the grain elevator environment. The sieve shaker was placed on a vibration cushion ≈0.5 m from the muffle box. Its operation was recorded on both inside and outside microphones. The shaker SPL was 77 dB between 1 and 10 kHz at the outside microphone.

Grain Elevator Noise and Insect Sound Measurements. Noise backgrounds were measured in the GISPSA facilities at the Bunge and Archer Daniels Midland grain elevators on the Mississippi River near New Orleans, LA. The backgrounds were recorded simultaneously with the B&K microphone inside and the Sennheiser microphone outside the muffle box. The GISPSA facilities were noisiest when the outside doors were open or the dust vacuum machines were operating. These conditions were recorded specifically as worst-case environments. Periodograms and SPLs were calculated by the digital signal processing procedures described above for sound attenuation measurements.

Sounds generated by 4th-instar *S. oryzae* larvae feeding inside wheat kernels were recorded inside the muffle box and inside the anechoic chamber using the B&K microphone-amplifier system and the digital recorder. The kernels were taken from cultures containing 4th instars, reared at 25 ± 1°C and 65 ± 5% RH by methods described in Vick et al. (1988b). The microphone fitted in the side of a cylinder (7.6 cm diameter by 7.6 cm long) filled with grain. The infested kernels were placed 3 cm from the microphone, near the center of the cylinder.

The DAVIS program (Mankin 1994) identified insect-generated sound bursts (a series of sound pulses) by their amplitude, duration, and ratios of spectrum levels in different frequency bands. The amplitude threshold was set at 0.1 V (after 80 dB amplification). Low-frequency noise occasionally rose above the amplitude threshold, but it could be

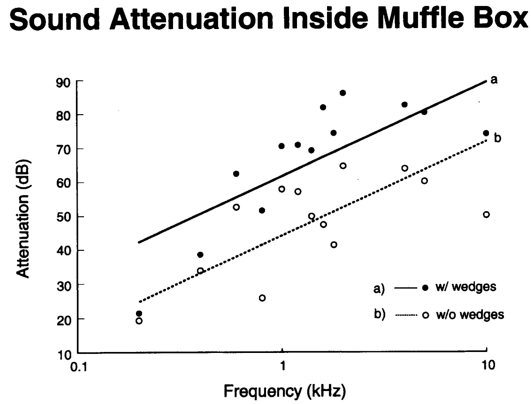

Fig. 2. Sound attenuation inside muffle box at different frequencies (a) with and (b) without foam wedges (15 cm thick). Attenuation (in decibels) = SPL outside − SPL inside box at specified frequency.

discriminated from insect bursts by its duration (usually <2 ms) and the ratio of high to low-frequency energy. A criterion that discriminated low-frequency noise from insect sounds was the ratio of maximum spectrum level in the frequency band between 5 and 9 kHz (*HIBANDMAX*) divided by the minimum level between 1 and 5 kHz (*LOWBANDMIN*). The minimum acceptable ratio of these 2 levels (*HIBANDMAX/LOWBANDMIN*) was set at 2. All signals of 2–8 ms duration with amplitudes >0.1 V and *HIBANDMAX/LOWBANDMIN* > 2 were counted as insect bursts. DAVIS generated periodograms of individual bursts and calculated mean SPLs. Because the bursts were often <0.1 s in duration, the burst periodograms were generated from 512-point spectra (20-ms averages) rather than the 4,096-point spectra (160-ms averages) used for the sound attenuation and grain elevator periodograms.

Results and Discussion

Whether a muffle box can satisfactorily shield an acoustic insect detection system in a grain elevator depends on the noise reduction, the signal-to-noise ratio at the acoustic sensors, and the spectral sensitivities of the sensors at different frequencies. To quantitate these factors, we consider below the spectral characteristics of the noise attenuation, the grain elevator noise levels, and the larva-generated bursts.

Muffle Box Sound Attenuation Characteristics. Fig. 2 shows the relationship between attenuation inside the muffle box (with and without the inner wedges) and the frequency of tones between 0.2 and 10 kHz produced by an external speaker. Below 1 kHz the attenuation decreased rapidly to 20 dB. Above 1 kHz the sound was attenuated 70–85 dB with wedges, but only 40–65 dB without wedges.

Table 1. Coefficients of best fit to regressions of muffle box noise reduction on logarithm of frequency

Parameter	Estimate	SE
A_{wedge}	−21.6	15.5
$A_{nowedge} - A_{wedge}$	−17.5	4.3
B	27.7	4.9

$A_{barrtype}$ (A_{wedge} for the muffle box with wedges and $A_{nowedge}$ without wedges), intercept; B, slope; n, 30; residual mean squared error, 128.

The results in Fig. 2 conform to the mass law of transmission loss for infinite barriers of uniform thickness (e.g., Vér and Holmer 1971),

$$R \approx \log(\rho_s f), \tag{1}$$

where R is the transmission loss in decibels, ρ_s is the surface density (mass density per unit thickness) in kg/m^2, and f is the frequency in hertz. According to equation 1, the transmission loss increases by 6 dB when the surface density of the barrier or the frequency of sound is doubled. The lines in Fig. 2 plot the regression equations of best fit calculated by SAS PROC GLM (SAS Institute 1988):

$$R = A_{barrtype} + B \log_{10}(f), \tag{2}$$

where R and f are defined in equation 1 and the regression parameters $A_{barrtype}$ (=A_{wedge}, or $A_{nowedge}$,) and B are listed in Table 1. Equation 2 has a coefficient of determination, $r^2 = 0.65$. A doubling of frequency increases the transmission loss by $27.7 \cdot \log_{10}(2) = 8.3$ dB, within 1.6 SE of the expected value of 6 dB. Also, the observed difference in attenuation between the regression lines, 17.5 dB, agrees with that expected from the wedge surface density stated by the manufacturer, $\rho_s = 4.9$ kg/m^2. To relate decibels of attenuation to surface density, note that from equations 1 and 2, and Table 1, $A_{wedge} - A_{nowedge} = B \text{ Log}_{10}(\rho_s)$, or $\rho_s = 4.3$ kg/m^2. Alternatively, the difference in attenuation expected from a layer of wedges with a surface density of 4.9 kg/m^2 is $B \log_{10}(4.9) = 19$ dB. The 2 estimates of attenuation difference agree within a standard error.

The deviations from the mass-law equation in Fig. 2 are not necessarily measurement errors, but are caused partly by resonances that occur in the different layers of the muffle box. The resonances occur at different critical frequencies and sound coincidence angles (e.g., Vér and Holmer 1971) that depend on the density, compressibility, and dimensions of each layer.

The measurements of sieve-shaker noise reduction (Fig. 3) corresponded well with the results of the speaker tests. The shaker noise was attenuated ≈51 dB between 0.1 and 10 kHz in the muffle box without wedges. The shaker was not loud enough to be detected at frequencies >1 kHz when wedges were present in the muffle box.

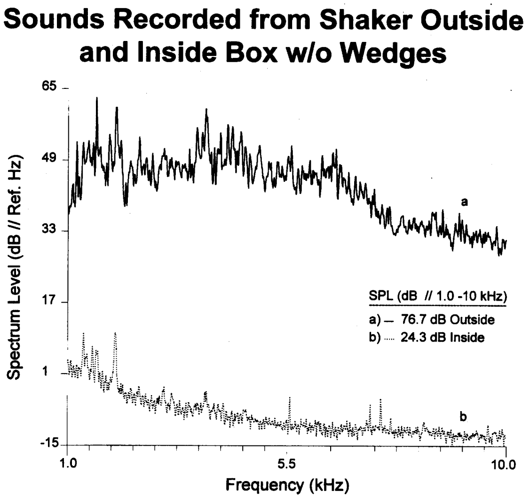

Fig. 3. Periodograms of sounds produced by a sieve shaker averaged over a 10-s interval between 1 and 10 kHz (a) outside and (b) inside muffle box (without wedges).

Grain Inspection Service, Packers, and Stockyard Administration Office Background Noise. The SPL of background noise inside the GISPSA offices was 50–80 dB between 0.1 and 10 kHz. A periodogram from a typical 10-s sample is shown in Fig. 4a. The muffle box reduced the background noise only ≈20 dB for frequencies <0.5 kHz, but the noise reduction was >60 dB for frequencies >1 kHz (Fig. 4b), as in the anechoic chamber. A comparison of SPLs at 10-min intervals over a 2-h period is shown in Fig. 5, referenced to different frequency ranges.

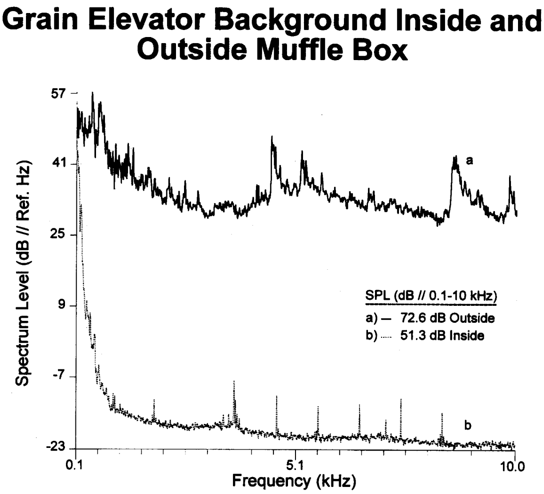

Fig. 4. Periodogram of background noise averaged over a 10-s interval between 0.1 and 10 kHz (a) outside and (b) inside muffle box at the Bunge grain elevator office.

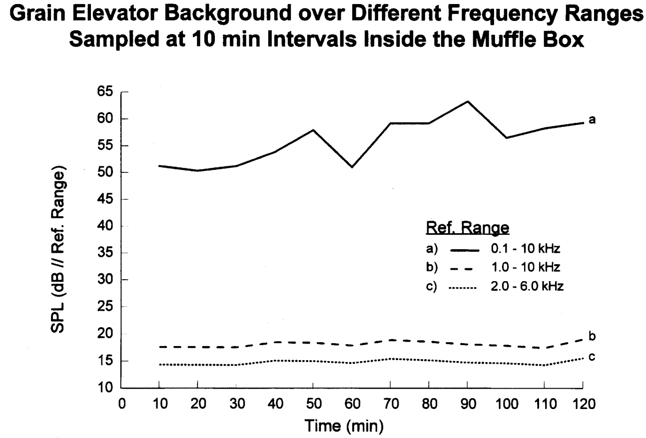

Fig. 5. Average background noise between (a) 0.1 and 10 kHz, (b) 1 and 10 kHz, and (c) 2 and 6 kHz inside muffle box at the Archer Daniels Midland and Bunge grain elevator offices, sampled over 10-s periods at 10-min intervals for 2 h.

The greatest levels of background noise occurred during dust vacuum blower operation. An example is shown in Fig. 6, which compares 10-s samples measured inside and outside the muffle box with the vacuum on and off. Most of this noise is concentrated at low frequencies, as can be seen in the comparison of SPL in dB//reference: 0.1–10.0 kHz (that is, decibels between 0.1 and 10 kHz, referenced to 20 μPa) with dB//reference: 1.0–10.0 kHz.

These results can be placed in perspective by comparisons with noise backgrounds in other environments. In Mankin (1994), noise SPLs were measured in dB//reference: 0.3–3.4 kHz for several different backgrounds: an anechoic chamber, 16 dB; a backyard at night, 30–40 dB; and a laboratory greenhouse with fans in operation, 70 dB.

Insect Sound Bursts. An example of a recorded larva-generated burst is shown in Fig. 7 (see also Hagstrum and Shuman 1995), and periodograms of bursts from 3 larvae are shown in Fig. 8 a–c. Bursts are variable in duration, usually 2–8 ms. In these and other insect recordings, we could identify only a few consistent spectral characteristics. The bursts usually had large spectrum level magnitudes between 2 and 6 kHz. Also, noise usually had a lower fraction of high-frequency energy than a burst (Fig. 8d). The mean SPL of 20 bursts each from 10 separate larvae, was 22.5 dB//reference: 1–10 kHz ± 0.3 dB SE (or 19.2 dB//reference: 2–6 kHz) at a distance of 3 cm in grain. The SPL decreases (or increases) by 6 dB for each doubling (or halving) of distance from the source. Analysis of variance (PROC ANOVA, SAS Institute 1988)

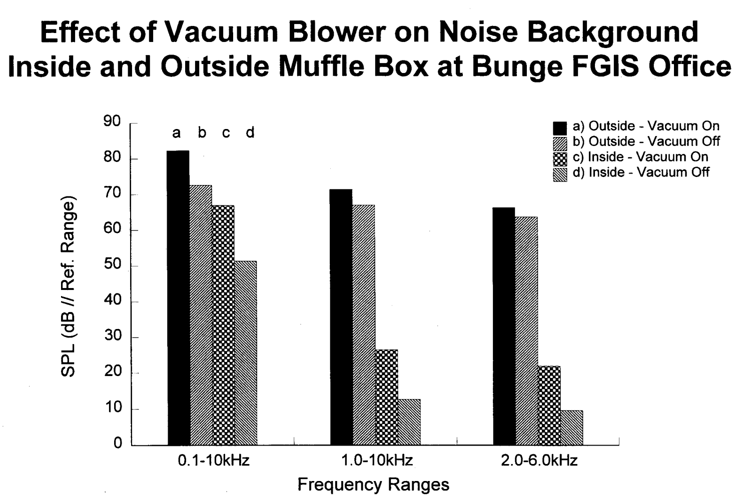

Fig. 6. Comparison of backgrounds at (a) high noise levels measured outside box, (b) typical levels outside box, (c) high noise levels measured inside box, (d) typical levels inside box, over different frequency ranges during a 10-s interval at the Bunge grain elevator office.

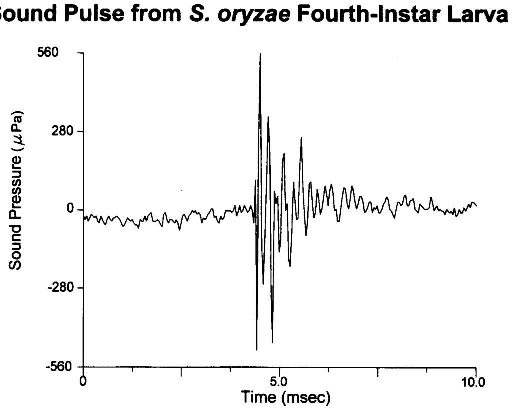

Fig. 7. Sound burst produced by a *S. oryzae* larva.

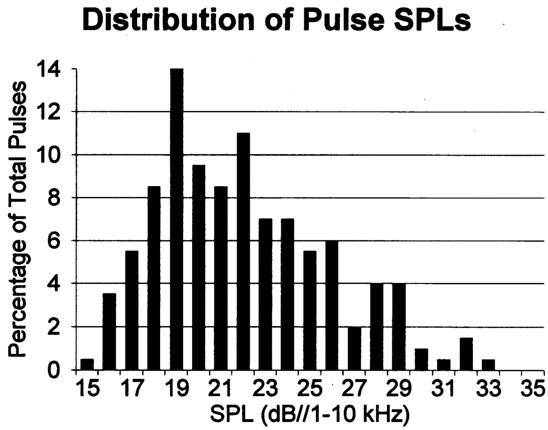

Fig. 9. Distribution of sound pressure levels of 20 bursts each generated by 10 *S. oryzae* larvae.

revealed no differences among larvae ($F = 0.46$; df = 9, 190; $P > 0.9$). The distribution of SPLs is shown in Fig. 9. The minimum SPL of identifiable bursts was ≈15 dB, and the maximum was ≈33 dB.

Minimum Shielding Requirements for Acoustic Sensors in Commercial Environments. Individual commercial environments have their own unique noise problems and shielding requirements, but a muffle box with shielding characteristics similar to the one we constructed will provide sufficient protection for acoustic sensors in most grain elevators. The 15- to 35-dB bursts generated by larvae have their greatest energy between 2 and 6 kHz (Fig. 8). The energy of a noise background is usually greatest for frequencies <1 kHz as in the 2 grain elevators where we recorded (Figs. 4 and 6). The signal can be filtered to eliminate noise for frequencies <1 kHz. With wedges, the muffle box provides 50–70 dB attenuation for frequencies >1 kHz, so an external noise would have to exceed 80–90 dB to interfere with insect detection.

Without wedges, the muffle box provides some protection (Fig. 3), but probably not enough to shield loud noises that occur when the office door is open or the vacuum is operating (Fig. 6). The 77-dB SPL sounds generated by a grain shaker could be detected in the muffle box without wedges at a level of 24 dB//reference: 1–10 kHz. Some larva-generated bursts exceed this level (Fig. 9), but many do not. If the wedges are required for satisfactory noise attenuation, the bulkiness of the muffle box may be reduced by other

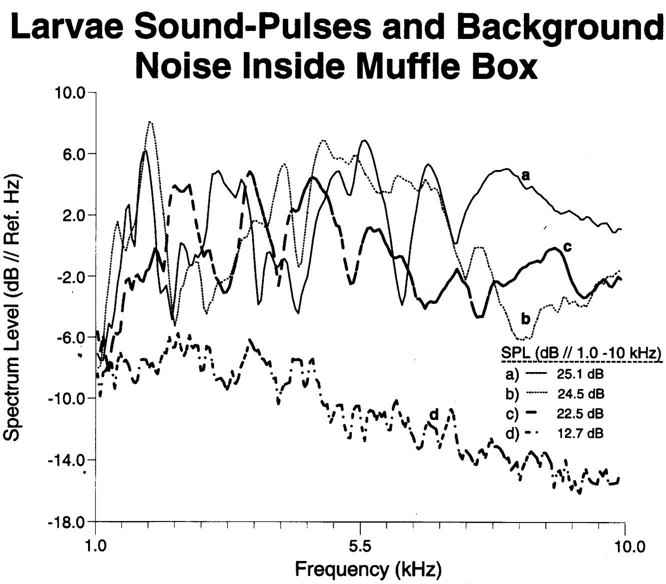

Fig. 8. Periodograms of (a) 53, (b) 72, and (c) 35 bursts from 3 different *S. oryzae* larvae, compared with (d) background noise level in muffle box.

methods in future versions. The wooden frames, for example, could be replaced with materials that have higher attenuation (e.g., aluminum or lead sheeting).

Acoustic devices that detect larvae can achieve a greater signal-to-noise ratio than shown in Fig. 9 by increasing the transduction gain of the acoustic sensors. The piezoelectric microphones used in the original acoustic location fixing insect detector (Shuman et al. 1993) are more sensitive to larva-generated signals at some frequencies between 2 and 6 kHz than the flat-sensitivity, reference B&K microphone used in this study. However, they are lower in sensitivity than the B&K microphone at other frequencies. Efforts are in progress to develop sensors of even greater sensitivity over the 2–6 kHz range of insect bursts.

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