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Shielding Against Noise Interfering with Quantitation of Insect Infestations by Acoustic Detection Systems in Grain Elevators

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ABSTRACT

Acoustic devices used to detect hidden insect infestations must be shielded from noise in most practical applications. One device developed specifically for use in a noisy environment, the Acoustic Location 'Fingerprinting' Insect Detector (ALFID), counts the numbers of insects present in grain samples from shipments being graded for export at commercial grain elevators. This report considers the performance of ALFID's noise-shielding components, which include an enclosure for passive reduction of ambient noise, and an electronic system for active detection and masking of sounds originating outside the grain sample container. Sound pressure levels (SPLs) of ambient noise are reduced inside the enclosure by 60–90 dB at frequencies between 1 and 10 kHz, with a reduction of ~6.5 dB per octave (frequency doubling). The active noise-masking system protects ALFID from loud ambient sounds not sufficiently attenuated by the enclosure. If the output from one of four sensors mounted on the outside of the grain sample container rises above a preset amplitude threshold, a signal is triggered that inhibits acquisition of insect sound data from sensors inside the container. In tests of the complete ALFID system at a grain elevator with ambient noise of 73 ± 10 dB re *20 μPa SPL, the mean rate of noise-mask triggering was 5.5 s^{-1}, inhibiting acquisition of insect sounds for only 3.9% of the total testing period. This level of performance is sufficient to enable successful operation of ALFID under such noise conditions. Published by Elsevier Science Ltd*

Keywords: insects, grain, noise, detection.

INTRODUCTION

Recent improvements in acoustic and digital signal processing technology have fostered development of devices for detecting hidden insect infestations. An example is the Acoustic Location 'Fingerprinting' Insect Detector (ALFID),[1–4] developed for the United States Grain Inspection Service, Packers and Stockyard Administration (GISPSA) to grade grain destined for export from commercial elevators. The ALFID includes an array of 16 sensors embedded in a grain sample container, electronic circuitry for the amplification of weak insect-generated sounds detected by the sensors, a noise shielding system, and a computer data acquisition and analysis system.[3,4]

The minimum noise-shielding requirements for ALFID were considered in recent studies that measured sound pressure levels (SPLs) and power spectra of sounds made by insects feeding inside grain kernels, compared with SPLs and spectra of the ambient noise in several GISPSA offices. Larvae of a common stored product pest, the rice weevil, *Sitophilus oryzae* (L.) (Coleoptera: Curculionidae), generated sounds 2–8 ms in duration at a mean SPL of 23 dB re 20 μPa (range: 15–35 dB), at distances of ~3 cm.[5] In contrast, the ambient noise in grain elevators ranged from 50 to 85 dB SPL.[5] However, the highest ambient noise levels occurred primarily below 1 kHz, due partly to noise abatement procedures adopted to reduce health and safety hazards,[6,7] while the larval sounds ranged primarily between 2 and 6 kHz. Although the larval sounds had no apparent resonant frequency which could be used for unambiguous identification,[8,9] much of the potential interference from ambient noise could be eliminated by filtering out signals below 1 kHz. We thus hypothesized that ALFID could detect larvae reliably if the sample container was protected in an enclosure that provided ~60 dB transmission loss above 1 kHz.

To test this hypothesis, a prototype muffle box[5] was constructed, adapted from designs of multi-layered noise-shielding enclosures used previously for insect acoustic detection.[10,11] The minimum number of layers necessary was estimated initially from published measurements of transmission loss through single noise reduction panels,[12–14] and specifications of the sound insulating properties of materials provided by commercial suppliers. The muffle box reduced the noise level by 70–85 dB between 1 and 10 kHz.[5] However, it was heavy (81 kg), difficult to maneuver, and samples could be processed only by removing ALFID from the muffle box. Experience with the muffle box led to a new design and the construction of a new enclosure.

The present version of ALFID has two levels of protection from ambient sounds, a passive noise-shielding enclosure, described below, and an active electronic noise-masking system, described in Shuman *et al.*[3] If a loud ambient sound is not attenuated sufficiently after passage through the passive shielding, the output from one of four sensors on the outside of the grain sample container rises above a preset amplitude threshold, activating a signal that blocks transfer of data to the computer for 7 ms. This report describes the design, construction, and noise reduction characteristics of the enclosure, and examines the performance of the active noise-masking system under conditions typical of a commercial grain elevator.

DESIGN

The initial enclosure design was a compromise among several competing requirements. (1) The ALFID container must be easily inserted into or removed from the enclosure for maintenance. (2) Grain samples must be easily loaded into or unloaded from the ALFID container when it is inside the enclosure. During testing, however, any opening to the outside that would permit a flanking path must be well sealed. Good sealing also is important for resistance to grain-dust infiltration. (3) The enclosure should be lightweight and mobile, but it must reduce external noise and vibration sufficiently to detect weak insect-generated sounds. (4) The external dimensions must be sufficiently narrow for the enclosure to fit through the standard 82-cm wide doors at GISPSA offices. Additional design considerations for the initial version were that it should be easy and inexpensive to construct.

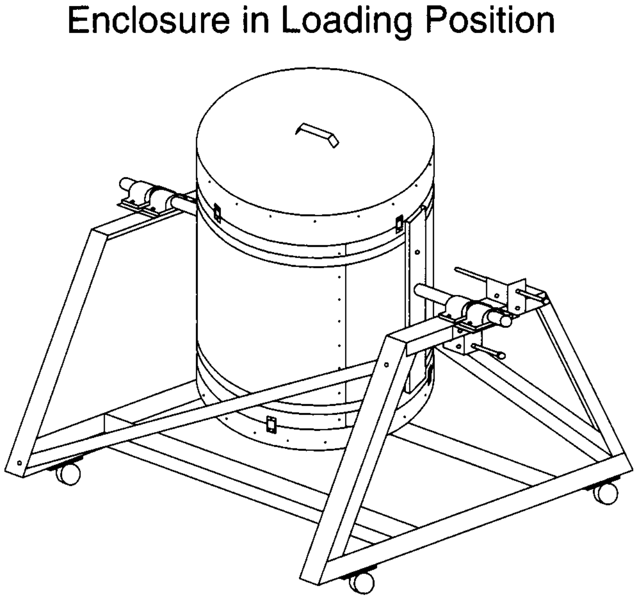

Fig. 1. Three-dimensional view of enclosure with top and bottom lids attached, held in vertical position for loading or moving.

Experience with the prototype muffle box[5] and a review of previously successful designs in the noise-control literature[12–15] suggested that, to reduce noise over a broad frequency range, the enclosure should include several different insulating layers with varying acoustic impedances. By constructing the enclosure as a series of shells, we could easily insert and remove the cylindrical grain sample container at one end. The other end of the enclosure could be sealed except for a small opening to load and unload grain samples. This would reduce exposure to noise and grain dust. The grain container would be protected from handling by wrapping it first in acoustic insulation and then sliding it into a smooth metal cylinder. A second, intermediate, shell of lead would provide more acoustic insulation, and an outer steel shell would provide protection and support for pivoting. The number of acoustic insulation layers between the metal shells would be determined as a compromise between the requirement of 60 dB noise reduction and the requirement of fitting the enclosure inside a doorway no wider than 82 cm.

CONSTRUCTION

Enclosure

The enclosure is fabricated from cylindrical shells of steel, acoustic foam, lead, and vinyl, all of which are easily purchased commercially. The outer shell is a 68.5-cm-diameter by 81-cm-long, 1-mm-thick steel cylinder. Removable steel lids are latched at the top and bottom of the shell (Fig. 1). The only other opening is a passage for the 1.9-cm-diameter cable between ALFID and the data acquisition system. The grain sample container,[3] 7.2 cm in diameter by 38.4 cm long,[3] is inserted into the enclosure by first wrapping it in two layers of 5.1-cm-thick polyurethane foam wedges (Illbruck Sonex, Minneapolis, MN) (Table 1). The assembly is pushed through the bottom opening into a steel cylinder, 30 cm in diameter by 43 cm long, 1 mm thick, centered in the outer shell (Fig. 2).

A funnel below the top lid permits rapid loading and unloading of grain. The aluminum funnel, 23 cm long and 0.4 cm thick, is 38 cm in diameter at the opening and narrows to 10 cm at the base where the funnel exits into the grain sample container. To reduce the transmission of vibrations, the funnel is not attached to the enclosure or to ALFID. It is held in place by pressure from a series of rings (Fig. 2) made of Illbruck Sonex, Prospec, vinyl barrier, Prospec (two rings), lead, and Prospec (three rings). A cone made from concentric layers of Sonex, Prospec, vinyl barrier, and lead fits between the funnel and the top lid.

Pedestal

The frame of a movable pedestal for the enclosure is constructed from eight 94-cm, two 46-cm, and two cross-bracing 109-cm bars of L-angle iron (Fig. 1). A 9.8-cm-diameter rubber caster is attached to each corner at the foot of the base. The attachment is cushioned with felt to reduce transmission of ground vibration, and after the enclosure is set up for testing, the casters are placed on 10-cm squares made from two 1.9-cm layers of polyethelyne sheathing and one layer of rubber.

TABLE 1
Thicknesses and Densities of Insulation Layers in the Enclosure

Material	*Thickness(cm)*	*Density(kg/m^3)*
Illbruck acoustical plastics:		
Sonex foam (open-cell polyurethane wedges)	5.08	32
Prospec foam (open-cell polyurethane sheet)	2.54	32
Prospec barrier (loaded vinyl sheet)	0.318	128
Prospec composite (urethane–vinyl–urethane)	3.49	41
Aluminum	0.04	2700
Steel	0.095	7800
Lead	0.318	11 300

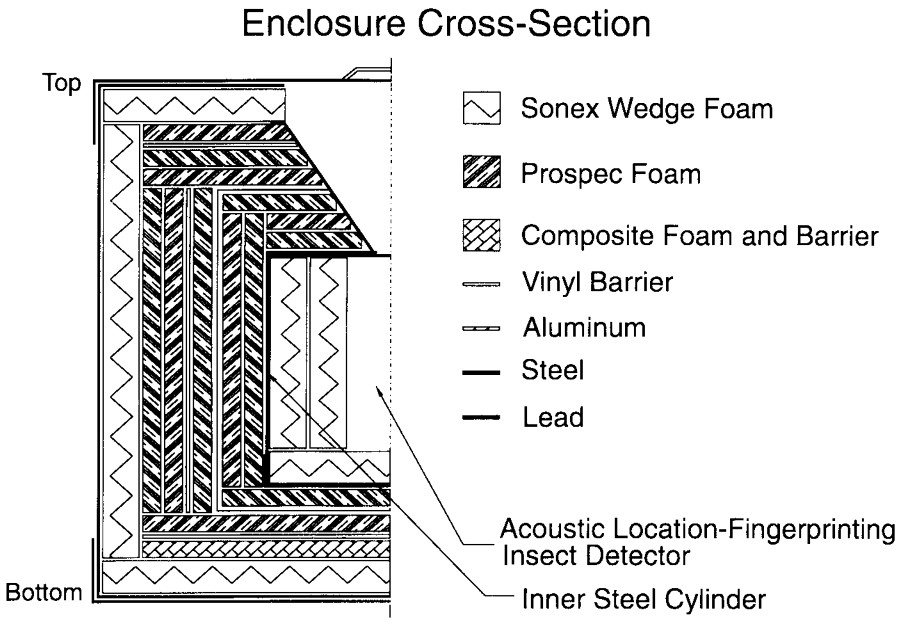

Fig. 2. Cross-section of enclosure, showing the position of ALFID and the layerings of steel, foam, lead, and vinyl barrier.

Two pillow-block bearings, 1.1 cm in diameter, are mounted on top of the frame (Fig. 2) to enable the acoustic enclosure to pivot on the pedestal. The bearings house a shaft welded to a U-beam, 7.62 cm wide by 61 cm long. The U-beams are welded to two 2.54-cm- by 0.32-cm-thick steel bands, which are welded to the top and bottom of the enclosure. The combined enclosure–pedestal system weighs ~70 kg.

A locking mechanism on the pedestal (Fig. 3) enables the enclosure to pivot among loading, testing, and unloading, fixed positions. A 1-cm-diameter, 25.4-cm-long pin at the side of the bearings locks the enclosure in a horizontal position. A pin below the bearings locks the enclosure vertically. To collect the grain sample after testing, a cardboard box is slid underneath the enclosure as it pivots down to the vertical position, and the retaining cone is removed from the ALFID container.

ANALYSIS OF NOISE ATTENUATION

Transmission loss spectrum

The attenuation of sound by the enclosure was measured in an anechoic chamber for sine-wave signals produced as separate tones between 0.2 and

Locking Mechanism

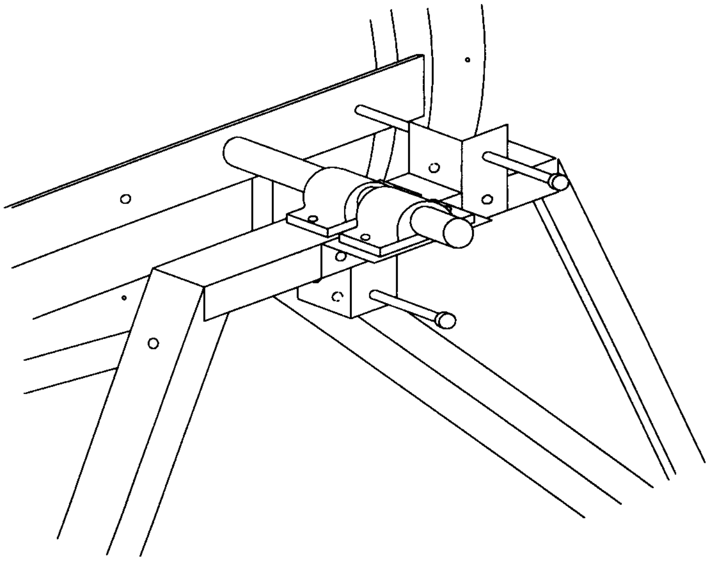

Fig. 3. Position-locking mechanism on pedestal. The pin at the side of the bearing holds the enclosure in a horizontal position. The pin below the bearing holds the enclosure in a vertical position.

10 kHz by a sweep generator (Wavetek model 185, San Diego, CA). A 200-W power amplifier (Audiosource model AMP One, Burlingame, CA) fed the signals to a 120-W speaker (JBL model 2441, Northridge, CA) set near the center of the chamber. The tones were detected by identical microphones (Brüel and Kjœr [B&K] model 4145, Nœrum, Denmark) inside and outside the enclosure, about 60 cm from each other and the speaker. The microphone inside the enclosure was pointed down along the axis of the enclosure, 10 cm from the bottom of the internal steel cylinder. The sound signals were bandpass-filtered between 0.2 and 15 kHz (Krohn-Hite model 3100, Avon, MA). Sound Pressure Levels were measured with B&K model 2610 amplifiers, calibrated in dB re 20 µPa. Signals from the microphone inside the enclosure were amplified 50 dB.

Transmission loss in high ambient noise

The performance of the enclosure was examined in a warehouse which had ambient noise levels of 65–80 dB SPL from operation of heating and cooling units in a corridor of insect-rearing incubators. To consider the effect of the grain sample container on shielding, a PVC cylinder dimensionally identical to the sample container was inserted into the enclosure in one series of tests. A B&K Model 4145 microphone was set 2 m from the enclosure, 1.2 m above the floor. A B&K model 4179 microphone was placed inside the enclosure, set as in the anechoic chamber. The amplified signals were recorded on a two-channel digital recorder (DAT) (Panasonic model SV-255, Matsushita Electric, New York, NY). For analysis, recorded signals were conditioned with a 12-kHz lowpass anti-aliasing filter and then digitized at 25 kHz by a 12-bit MetraByte (Keithley/MetraByte Inc., Taunton, MA) DAS-16G A/D board installed in a 80486 microcomputer. Spectrum periodograms were constructed using DAVIS, a custom-written signal processing and spectral analysis computer program.[5] Periodograms were generated from 60-s means by averaging 4096-point spectra over consecutive 100-ms increments.

EVALUATION OF THE NOISE-MASKING SYSTEM

The operation of the noise-masking system was evaluated in the laboratory and in the GISPSA office at the Bunge grain elevator near New Orleans, LA. To ensure masking of any ambient noise that could be detected by the 16 sensors inside the grain sample, the amplitude threshold was purposely set just above the level that activated continuous triggering. In three separate 10-min trials, the masking trigger signal[3] and the ambient noise detected by a portable microphone (Sennheiser model MKH 4161, Old Lyme, CT) were recorded on separate channels of the DAT. The recordings were made in different ambient noise environments to determine what external signals were most likely to inhibit acquisition of signals from the grain sample container. In each of these recordings, the grain sample container was loaded with a 1-kg wheat sample, and a single kernel infested with a rice weevil was inserted as described in the analysis of the ALFID insect-counting algorithm,[4] to determine if the ALFID system was counting correctly the number of insects present in the grain sample.

The recordings of noise-masking trigger signal and the ambient noise both were analyzed using the DAVIS signal processing software.[5] The triggering frequency was calculated as the inverse of the interval between consecutive triggers. Ambient signals were compared against the trigger record, with particular attention to times where the triggering frequency exceeded $40\,s^{-1}$. Longer-term average measurements of the ambient grain elevator noise were obtained with a sound level analyzer (CEL Instruments model 593, Herts, UK).

Tests of the noise-masking system also were conducted in a quiet laboratory at 65 dB re 20 μPa SPL for frequencies between 0 and 10 kHz. In two 10-min trials, the trigger signal, outputs from the four sensors on the outside of the grain sample container, and the ambient noise detected by a B&K model 4145 microphone, were recorded on six channels of a DAT (Sony PC216a, Sony Magnescale Inc., Orange, CA). Analysis of masking trigger times and spectral analyses of sensor and microphone outputs were performed and periodograms were generated as described in above, using the custom-written DAVIS software.[5]

RESULTS

Based on results in the literature and preliminary testing in the laboratory, it was expected that the passive noise reduction system would reduce all but the loudest sound impulses below the threshold of the noise-masking system. Tests of the complete system at a Bunge Corporation grain elevator facility near New Orleans, LA, verified these expectations. An example is from a recording that included an event of grain dropping through a chute into the GISPSA office. Grain transfer and sieving operations are among the loudest noises typically encountered in these offices. Representative spectra of these sounds and a more typical background are shown in Fig. 4. The rate of noise mask triggering in a 30-s period before this event was $5.7\,s^{-1}$. During the event, the rate increased to $11.1\,s^{-1}$. However, the ambient noise did not inhibit successful acquisition and analysis of insect sound data during the test.

Loud sounds, such as those in Fig. 4, or sudden impact events like doors closing, grain buckets hitting floors, etc., occupied only a small proportion of the total recorded period. Such events usually activated the noise-masking trigger, but the number of triggers per event was a small fraction of the total number of triggers owing to the low setting of the noise-masking amplitude threshold.

Transmission loss spectrum

In the anechoic chamber, the enclosure attenuated 1-kHz tones by ~60 and 10-kHz tones by ~90 dB. The relation between attenuation inside the enclosure and the frequency of external tones is shown in Fig. 5. The pattern of attenuation conforms to the mass law of transmission loss[15]

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

where R is the transmission loss in dB, ρ_s is the surface density (mass density per unit thickness) in kg/m^2, and f is the tone frequency in Hz. According to eqn 1, the transmission loss increases by 6 dB when the density of the

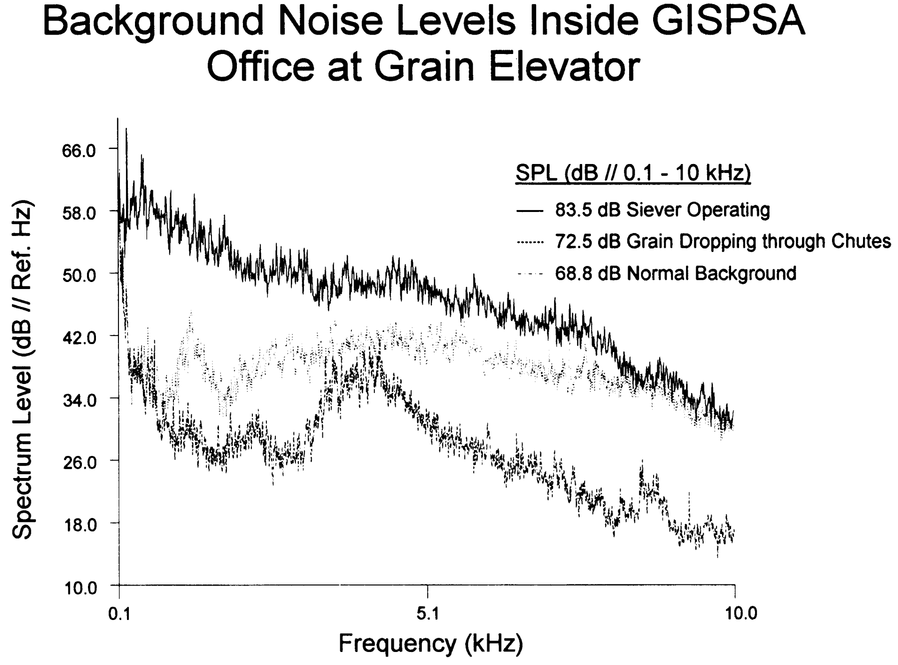

Fig. 4. Examples of sound events typically occurring inside a GISPSA office at a grain elevator, including noises of grain dropping through chute entering building and a grain siever in operation. The spectra were generated from 60-s means by averaging 4096-point discrete Fourier transforms over consecutive 100-ms increments.

enclosure (see Table 1 for densities and thicknesses of the enclosure shells), the frequency of sound, or their combination is doubled. The line in Fig. 5 plots the regression equation of best fit, calculated by SAS PROC GLM[16]

$$R = -2.4 + 21.8 \log_{10}(f) \tag{2}$$

where R and f are defined in eqn 1. has a coefficient of determination, $r^2 = 0.75$, and the standard errors of intercept and slope are 8.68 and 2.54, respectively. A doubling of frequency increases the transmission loss by $21.8 \log_{10}(2) = 6.55$ dB, within a standard error of the expected value, 6. The deviations from the mass-law equation in Fig. 5 are not necessarily measurement errors, but are due partly to resonances that occur in the different layers of the enclosure. The resonances occur at different critical frequencies and sound coincidence angles[12,15] that depend on the density and compressibility of each layer.

Enclosure performance in a high-noise environment

The ambient sounds with the greatest potential to interfere with the operation of ALFID are not long, continuous tones but short, broadband pulses,

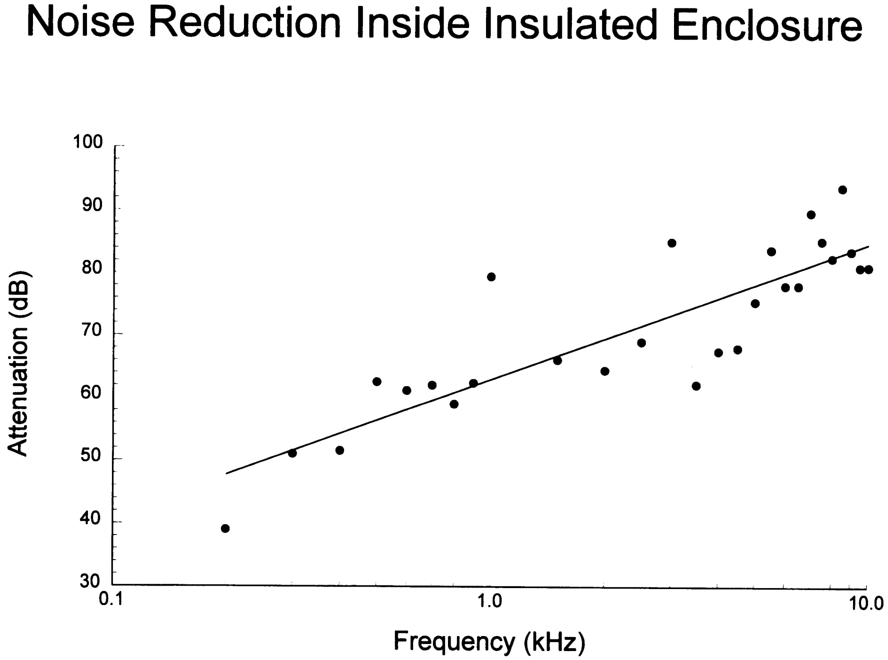

Fig. 5. Spectrum of noise reduction across frequency inside insulated enclosure.

similar in temporal and spectral structure to insect feeding and movement sounds. For this reason, before the complete ALFID system was tested in a grain elevator, we conducted separate tests of the enclosure in a warehouse with constantly cycling, noisy equipment. Although the warehouse had a high ambient noise level near 76 dB, the mean signal levels inside the enclosure remained near the threshold of detectability by the B&K Model 4179 microphone (Fig. 6).

When a PVC cylinder dimensionally identical to the grain sample container was inserted into the enclosure, several small peaks appeared in the spectrum (Fig. 6b). This indicates the potential for resonances within the cylinder (e.g. at frequencies that are multiples of the speed of sound divided by cylinder length, $340\,\mathrm{m\,s^{-1}}/0.384\,\mathrm{m} = 880\,\mathrm{Hz}$). These resonances are reduced when grain is present in the sample container because of the high attenuation coefficient of grain, $> 2\,\mathrm{m^{-1}}$.[17,18]

In 60-s averages, the noise level inside the enclosure at frequencies > 1 kHz was less than 16 dB re 20 μPa, and at many frequencies, the signal level was

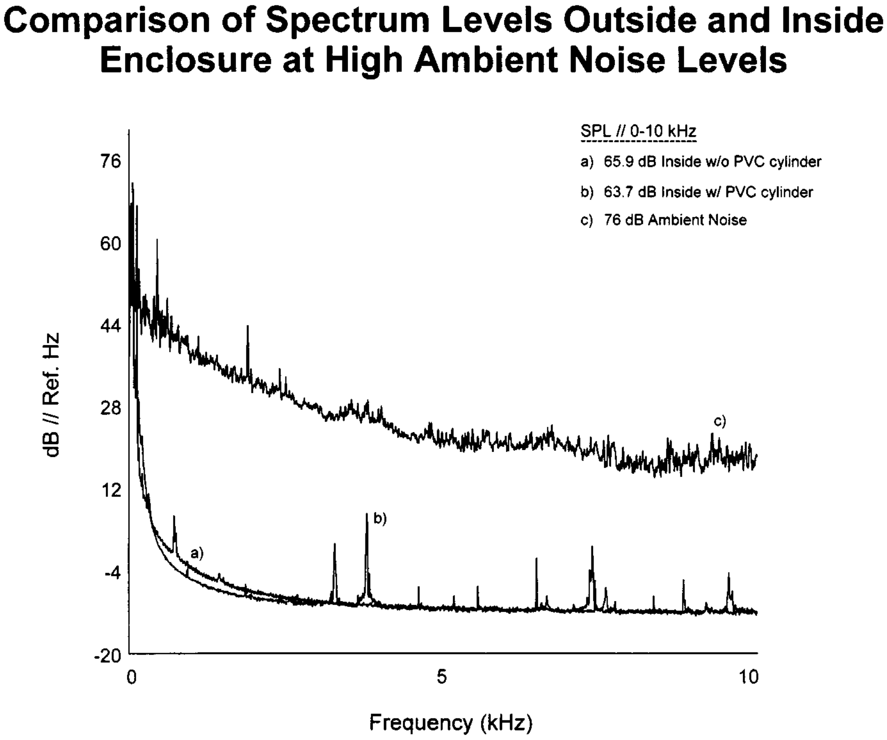

Fig. 6. Spectra of ambient noise in a warehouse: (a) measured by a microphone inside enclosure; (b) same as in (a) with a microphone suspended inside a cylinder the same dimensions as the ALFID grain sample container; and (c) measured by a microphone outside the enclosure.

below the sensitivity of the internal microphone. It was thus expected that the enclosure would provide satisfactory shielding for the ALFID in the field, except for a few loud broadband impulses that could be blocked by the noise mask trigger.

Noise-masking trigger response

The mean rate of triggering increased from 4.4 s^{-1} in the 65 dB SPL ambient noise of the laboratory to 5.5 s^{-1} in the 73 dB SPL ambient noise of the Bunge grain elevator. Measurements by the CEL sound level meter over a 16-h period in the grain elevator yielded a mean of 73.2 dB, a maximum of 82.6 dB and a minimum of 63.4 dB SPL re 20 μPa. Given that each occurrence of a trigger inhibits the acquisition of signals for 7 ms, the percentage of time for which the ambient noise was loud enough to inhibit data acquisition was 3.9% in the grain elevator and 3.1% in the laboratory. The distribution of rates $> 10\,s^{-1}$ in five 10-min trials is shown in Fig. 7 for the laboratory and the grain elevator. Ambient noises at these levels did not

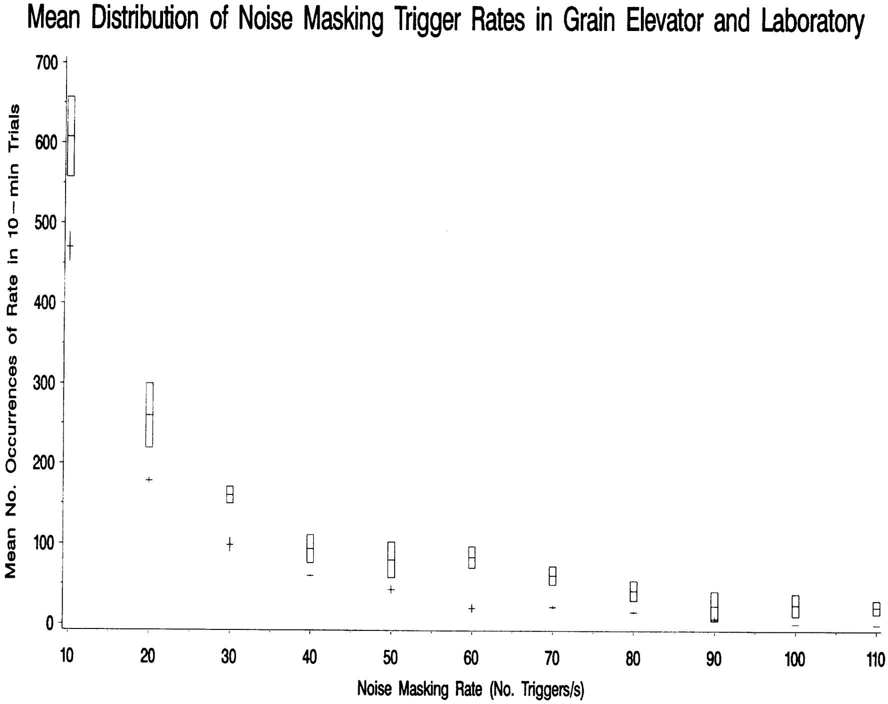

Fig. 7. Mean distribution of the noise masking trigger frequency in 10-min trials in the Bunge grain elevator (means denoted by dashes, and standard errors by bars) and the laboratory (means denoted by dashes and standard errors by vertical lines).

interfere with the counting of insects. The ALFID algorithm[4] correctly counted the infested insect in all three of these tests.

Examination of the external microphone recordings revealed that the occurrence of a high rate of triggering, $>40\,s^{-1}$, usually corresponded to an observable sound above the ambient background, both in the grain elevator and the laboratory. However, during periods where the rate of triggering was less than $30\,s^{-1}$, there was usually no obvious sound above the ambient background. The number of events with a triggering rate $>40\,s^{-1}$ was 431 per 10-min trial in the grain elevator and 170 in the laboratory. The optimal setting for the amplitude threshold remains to be determined, but it probably will be set higher in future testing to decrease the fraction of time in which potential acquisition of insect sounds is inhibited.

Many events that activated the noise-masking trigger had significant vibrational components which were transmitted through the building structure to the enclosure pedestal. Light tapping on the enclosure also activated the noise-masking trigger. These results suggest that some sounds detected by the noise-masking sensors on the outside of the grain sample container may not have been transmitted ambient sounds, but instead were internal sounds generated by vibration-induced settling movements in the different insulation layers.

DISCUSSION

The design of the new enclosure for ALFID is an improvement over the previous version[5] in that it provides for easy loading and unloading of the grain sample container without sacrifices in noise reduction above 1 kHz. The enclosure provides 60–90 dB of noise reduction between 1 and 10 kHz, and the small number of sounds loud enough to be detected at the grain sample container after traversing the enclosure can be easily blocked by the noise-masking system. The weight of the new enclosure is near the practical limits of portability, so an increase in the passive noise reduction characteristics of the system is probably not feasible except in a permanent installation.

If necessary, additional electronic filtering can be used to provide higher levels of noise reduction than is provided by the sound-insulated enclosure. Much of the background noise intensity is at frequencies below 2 kHz, but insect-generated sounds have the greatest intensity between 2 and 6 kHz. Consequently, ALFID may be operable at background levels >80 dB, depending on the ambient noise spectrum.

In environments where the position of ALFID is fixed relative to the locations of major noise sources, attenuation can be increased by attaching patches of acoustic materials inside the enclosure at points of resonance.[19] The selective use of patching would permit a reduction in the total thickness, weight, and cost of insulation.

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