

DETECTION OF WHEAT KERNELS WITH HIDDEN INSECT INFESTATIONS WITH AN ELECTRICALLY CONDUCTIVE ROLLER MILL

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ABSTRACT. A laboratory roller mill system was modified to measure and analyze the electrical conductance of wheat as it was crushed. The electrical conductance of normal wheat kernels is normally low and fairly constant. In contrast, the electrical conductance of wheat kernels infested with live insects is substantially higher, depending on the size of the larvae and the resulting contact of the crushed larvae between the rolls. This instrument was designed to detect internal insect infestations in wheat that has a moisture content of 13.5% or less. The laboratory mill can test a kilogram (kg) of wheat in less than 2 min and 100 g in less than 10 s. Hard red winter and soft red winter wheat containing larvae of rice weevils and lesser grain borers of a variety of sizes were tested. On average, the instrument detected 8.3 out of 10 infested kernels per 100 g of wheat containing the larger sized insects (fourth instar or pupae). Kernels infested with medium-sized larvae (second or third instar) were detected at an average rate of 7.4 out of 10 infested kernels per 100 g of wheat. Finally, kernels infested with the small-sized larvae (first or second instar) were detected at a rate of 5.9 out of 10 infested kernels per 100 g of wheat. Under reasonable grain moisture contents there were no false positive errors, or noninfested kernels classified as insect infested. The cost of the mill is low and can lead to rapid and automated detection of infested wheat.

Keywords. Rice weevil, Lesser grain borer, Grain testing.

Grain kernels infested by insects may show no indication on their exterior, but often contain hidden larvae. Although grain is always inspected for insect infestations upon shipping and receiving, many infested samples go undetected. Storey et al. (1982) obtained wheat samples from 79 U.S. elevators. Initially, 4% of the samples contained evidence of insect infestations. However, after incubating the samples for 4 to 6 weeks, it was found that 16% of the samples actually contained insects. If infested grain is added to bulk storage and transportation vessels, the insects may multiply and infest the bulk further within several weeks. U.S. grain standards consider wheat infested if two or more live insects are found within a 1-kg sample (FGIS, 1997). However, this does not take into consideration immature insects that may be living inside the kernels of grain and cannot be readily detected.

Many methods of detecting infested wheat have been developed but none has seen widespread use because of expense or inadequate accuracy, or both. Some of these methods include staining the wheat to detect weevil egg plugs (Milner et al., 1950), microphones for listening to insects feeding (Hagstrum et al., 1990), single kernel compression testing (Pearson et al., 2003), single kernel near

infrared measurements (Dowell et al., 1998), and X-ray imaging (Karunakaran et al., 2004; Fornal et al., 2007). Single kernel methods and X-ray methods can detect infested wheat fairly well, but the sample size is small and the equipment rather expensive. Detection of insect-infested wheat is a particularly difficult problem because infestation levels are usually quite low. A common low level of infestation that grain handlers wish to detect is five infested kernels per 100 g (3000 kernels) (Becker, 2002). This represents an infestation rate of 0.17%. At infestation rates this low, false positives - uninfested kernels classified as infested - become a serious problem for any system to gain widespread acceptance.

The objective of this work was to develop and test a system that could rapidly detect infested wheat from 1-kg wheat samples. Pearson et al. (2003) found that wheat infested by insects could be detected by conductance as the kernel was being crushed. However, this method was based on measurements of one kernel at a time at a rate of 120 kernels/min, which is too slow for practical use. The method used in this current study utilized a small roller mill that has a throughput of approximately 30,000 kernels/min (1 kg/min). Circuitry was added to the mill to measure the conductance of the material passing between the rolls. It was found that when most infested kernels are crushed, the fluid from the larvae contacts the rolls and the higher conductance of the fluid causes a distinguishable voltage signal across the rolls, indicating the infestation.

MATERIALS AND METHODS

MILL CONSTRUCTION

The laboratory roller mill consisted of two, 8-cm diameter by 10-cm wide steel rolls, which were mounted on a 2.5-cm

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diameter steel shaft. The rolls were fabricated in the USDA-ARS-GMPRC machine shop. The surfaces of the rolls were knurled with a straight knurling tool having 22 teeth/in. (08680191, MSC Industrial Supply Co. Elkhart, Ind.). The drive roll was coupled directly to a 1/2-hp, 115-Vac gearmotor operating at 30 rpm (22794D, Dayton Mfg, Niles, Ill.). This roll was mounted onto aluminum blocks and was electrically grounded through the gearmotor. In contrast, the slave roll was mounted onto a Delrin block, which electrically isolated the roll from the drive roll. Both the aluminum and Delrin roller mount blocks had roller bearings press fit into them for each roller shaft. A wheat sample was simply played in a hopper above the rollers and the gearmotor started to initiate the test. A 5-Vdc supply was electrically connected to the slave roll via a motor brush that contacted the roll. An electrical diagram of the conductance circuit is shown in figure 1. An op-amp voltage follower was used to electrically isolate the conductance circuit from the input of the oscilloscope.

Preparation of Infested Samples

Two classes of wheat, hard red winter (HRW) and soft red winter (SRW), from the 2006 harvest year were tested. The HRW was obtained from a grain elevator in Kansas and presumably contained mixed varieties, while the SRW was obtained from a seed company in Missouri. The lots were passed through a Carter Dockage tester by using the specified dockage configuration for wheat. The moisture levels of the lots were determined using the whole-grain oven drying

method (ASABE Standards, 2006). The lots were split and the moisture content adjusted to two levels. One portion of the wheat was dried to 10.5% to 11% by thin layer drying at ambient conditions of 30°C and 45% relative humidity. The second portion of the wheat was tempered to 13.0% to 13.3% by adding the required additional water, tumbling, and then storing the samples in a sealed container for an extended period before use.

Using both the HRW and SRW wheat, insect colonies were established with two species of common stored grain insects - the rice weevil [*Sitophilus oryzae* (L.)] and the lesser grain borer [*Rhyzopertha dominica* (F.)]. Approximately 300 adult rice weevil and lesser grain borer were added to 500-g samples of 13% wheat. The colonies were allowed to incubate for 4 to 5 weeks in a chamber set at 27°C; the adults were then removed.

A real time X-ray unit (MX20-DC44, Faxitron X-ray Corp., Wheeling, Ill.) was used to generate X-ray images of 10- to 20-g sub-samples of wheat kernels. Kernels were then selected based on the size of the insect larvae within the kernel. The infested kernels were picked and sorted into three size categories: small, medium, and large. The small larvae occupied an area that was approximately 10% of the kernel's two-dimensional (2-D) view. This size of larvae corresponds with the first or second instar maturity stage. The medium larvae corresponded to the second or third instar maturity stage and occupied between 10% and 25% of the kernels 2-D view. The large larvae, corresponding to the fourth instar or pupal stages (Sharifi and Mills, 1971), occupied over 25% of the 2-D view. Over 3000 infested seeds were picked and sorted for the entire experiment. Example X-ray images of small, medium, and large larvae are shown in figure 2.

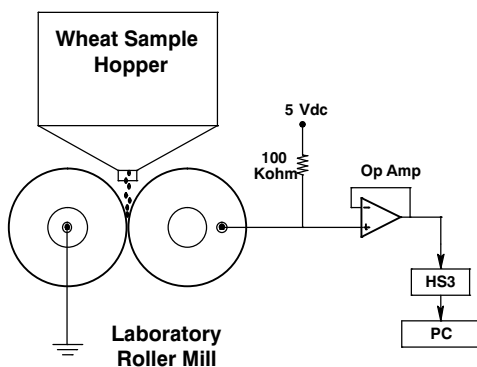
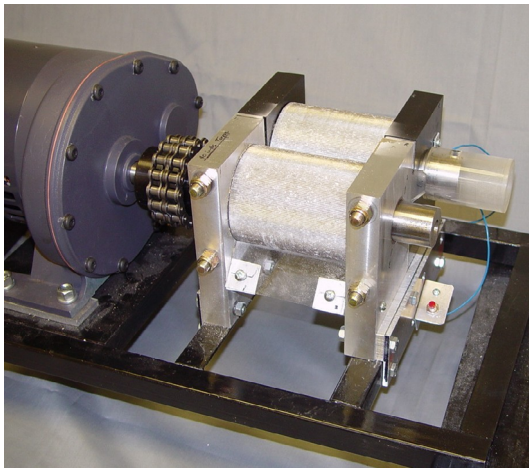


Figure 1. Photograph of the laboratory roller mill (without the sample hopper) and electrical schematic of conductivity circuit and data acquisition system. Note the Delrin (black) mounts for the slave roll.

Mill Testing

Preliminary experiments tested noninfested HRW and SRW wheat at seven levels of moisture, ranging from 11% to 17%. For this test, 500-g samples were conditioned at each moisture level; three 100-g subsamples from each moisture level were then run through the mill. Thus, 21 tests were performed for both SRW and HRW wheat. The conductance voltage was computed over 5 s of data per test, then the average was determined for the three trials.

For the detection of insect-infested wheat, an experiment was conducted with the following factors: HRW and SRW wheat, 11% and 13% bulk moisture contents, rice weevil and lesser grain borer insects with three larval size categories (small, medium, and large), and mill gaps of 0.46 and 0.71 mm (0.018 and 0.028 in.). Each trial used approximately 100 g of wheat (approximately 3000 kernels) with 10 infested kernels of a given size larvae mixed into the sample. For the 0.46-mm roll gap, each test combination



Figure 2. X-ray image of internally infested wheat showing examples of large, medium, and small larvae.

(wheat, moisture, larvae species, larvae size, and gap) was repeated 10 times for a total of 240 tests. For the 0.71-mm roll gap, only rice weevils were used, only 13% moisture wheat was used, but both HRW and SRW were studied with all three insect sizes. Each wheat-insect size combination was tested 10 times for a total of 60 tests at the 0.71-mm gap.

A secondary set of tests were performed with one infested kernel mixed with 50 g of uninfested HRW at 11% moisture. Only the 0.46 mm mill gap was used in these tests. A total of 100 of these tests were performed, 50 with large rice weevil larvae and 50 with medium rice weevil larvae. The purpose of these tests were to compare the recognition accuracy with a very low level of infestation (2 per 100 g) with those infested at a moderate level of 10 per 100g from the main tests.

To test the amount of false positive classifications, or number of un-infested kernels counted as infested, 47 control samples with no added infested kernels were run through the mill. These samples comprised both HRW and SRW wheat at 11% and 13% moisture.

To determine the effect of high moisture kernels (15-17%) that might be mixed with normal moisture kernels (11-13%), a set of 26 100-g samples, comprising either HRW or SRW at 11% or 13% moisture, were mixed with 10 kernels of the same class but tempered up to 15% or 17% moisture. This test was also repeated after storing the high moisture kernels together with the lower moisture kernels for 24 h.

Each trial required 10 s of data collection, although the time to crush 100g was usually less than 7 s. Data were collected by a PC/oscilloscope interface electronics and software (model: HS3, TiePie Engineering, Sneek, The Netherlands) and a laptop computer (model: 4100xdvd, Toshiba, Toyko, Japan). The data sampling rate in the oscilloscope was set at 1000 Hz. The signal from each 100-g test was saved for analysis at a later time. The voltage level of the wheat maintained a steady level between 4.5 and 5 V depending on the moisture content of the wheat. However, the insect-infested kernels caused an abrupt dip in the voltage signal due to the insect fluid, which created a higher conductance between the mill rolls.

Conductance Signal Analysis and Detection of Infested Wheat Kernels

A program was created to analyze the voltage signal and to count the number of voltage dips caused by the insect-infested wheat kernels per each 100-g trial. The program simply input the complete data file containing the digitized voltage signal, and then computed the signal gradient using a 5-millisecond interval (five data point gap) as,

$$\text{grad}(x) = \text{signal}(x+5) - \text{signal}(x) \quad (1)$$

where $\text{grad}(x)$ is the gradient (in volts) of the signal at data point x computed from the raw signal at points x and $x+5$.

Examples of a raw signal and the gradient signal from SRW wheat at 13% moisture are shown in figure 3. While moist grain caused the voltage across the mill rolls to drop to about 4.5 V, the infested kernels dropped the signal below 3 V in most cases.

From the raw signal in figure 3, there are seven easily discernable dips that were caused by infested kernels. Five of these dips fall below 3 V and one only drops close to 4 V. Two of the dips may be due to more than one infested kernel being milled at the same time. The dip at 3.25 s is possibly due to two infested kernels, while the dip located at 3.6 s, is likely due to two or three infested kernels being milled at the same time. The dip at 3.6 s is wider than the others and contains two or three confounded peaks very near each other. While there were 10 insect infested kernels in the sample, only eight can be detected. The gradient signal alleviates the effect of the voltage drop due to moisture in the grain, while highlighting the dips caused by the infested kernels. The absolute value of the downward slope of each dip due to infested kernels was always greater than the upward slope. This is probably due to the insect fluid abruptly short-circuiting the mill rolls. Thus, the negative gradient was used for the detection of infested kernels.

In figure 3, the minimum gradient for the smallest dip, located at 4.7 s, is 0.48 V. In contrast, the minimum signal amplitude of the gradient signal in regions where there were no voltage dips due to infested kernels was 0.07 V. It was

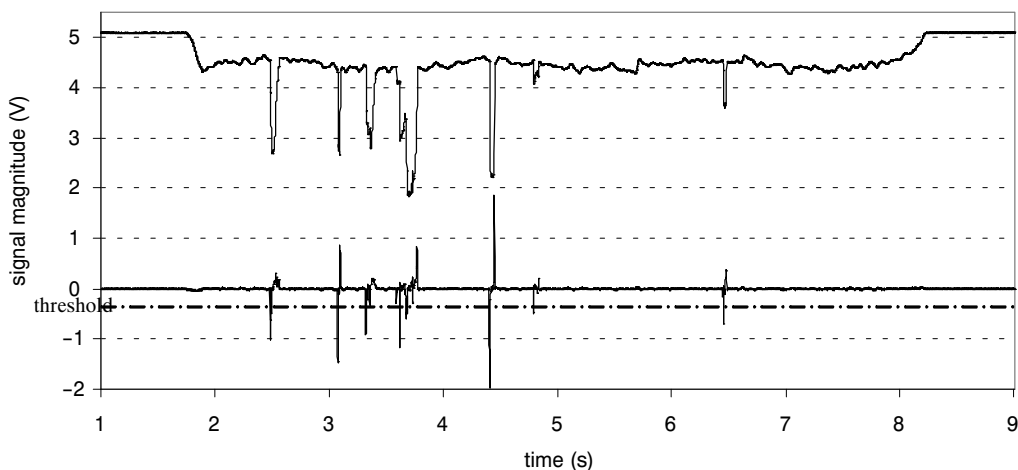


Figure 3. Example signal (top) and gradient (bottom) from a 100-g sample recorded of SRW wheat, 13% moisture, and medium-sized lesser grain borer larvae. The first second of the recording is not shown. Note that the gradient signal helps filter out effects from the moist grain, while maintaining discernable signals due to the voltage drops caused by infested kernels. The -0.3-V threshold for counting a gradient signal as an infested kernel is shown as the horizontal dash-dot line.

determined by trial and error that the use of a minimum gradient of 0.3 V could properly detect over 90% of the dips caused by infested kernels, while incurring no false positive dips in any of the samples.

The signal gradient was sequentially processed from earlier to later. When the gradient level dropped below -0.3 V, an insect infestation was counted and the minimum of the corresponding dip in the raw signal was recorded. The minima were found by detecting the minimum signal value from the 85 points after the gradient dropped below -0.3 V. The 85-point duration was found, by trial and error, to be sufficient to avoid counting of two peaks from one single peak. In some cases (approximately 1%), this caused a dip to be missed where two kernels were being compressed in the mill at the same instant. However, by visual inspection, no dip due to a single infested kernel was ever counted as two infestations.

RESULTS AND DISCUSSION

CONDUCTANCE CHARACTERISTICS OF VARIOUS BULK MOISTURE CONTENTS

For the preliminary conductance test, data were collected for grain at several different bulk moisture contents. The conductivity varied significantly with grain moisture content. However, the instrument was calibrated for wheat less than 13.5% moisture (wet basis). Wheat is usually stored and traded at moisture contents less than 13.5% because this moisture level is considered the upper limit for the long-term safe storage of wheat. Mold growth is rapid at levels above 13.5% (Christensen and Meronuck, 1986).

Figure 4 shows the voltage signals for a range of wheat moistures. Wheat at 13.5% moisture and lower produced signals that changed less than 1.0 V from the baseline. Higher moisture grain produced signals with much more change.

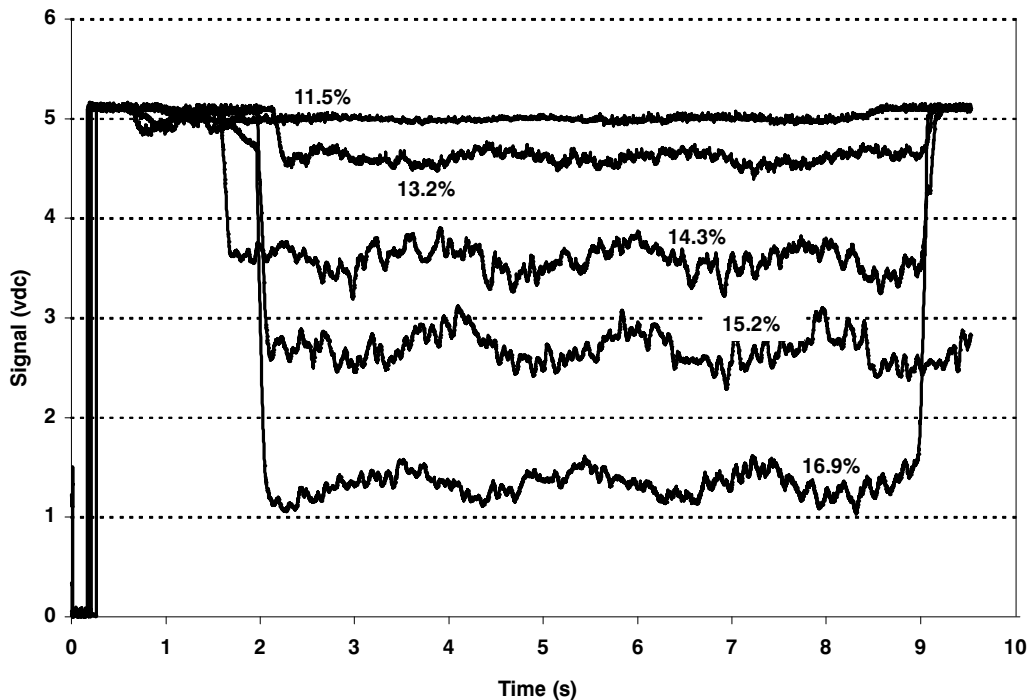


Figure 4. Conductance signals for various moisture contents between 11.5% and 17%.

Figure 5 shows average voltage drops for HRW and SRW wheat at seven moisture contents. Again, the trend lines show a significant relationship between grain moisture and the voltage signal. The HRW wheat was slightly more conductive than the SRW for a given moisture level. Moreover, the signal drop for wheat at 13.5% moisture is less than 1 V.

Recognition Rates of Infested Kernels

Overall recognition rates of infested kernels obtained by using the computer program are listed by insect size, wheat class, and moisture content in tables 1 through 3.

As expected, recognition rates increased for larger insect larvae. Rice weevils tended to be larger than lesser grain borers so the recognition rates for rice weevils were, on average, 10% higher. For both species of insects, recognition rates increased as the insect larvae size increased. The

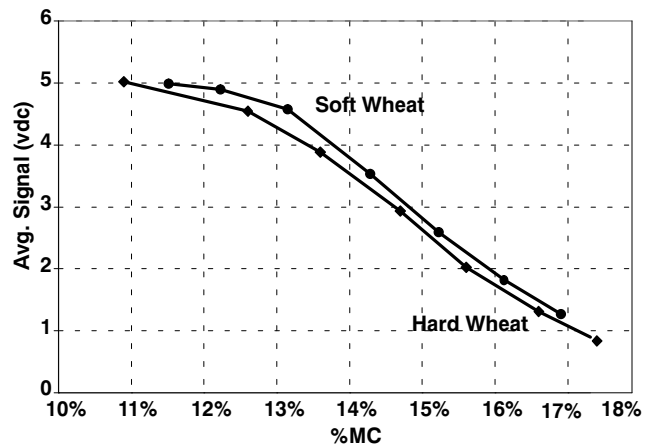


Figure 5. Voltage drop due to bulk wheat moisture content. Note that 13.5% moisture causes less than 1-V drop.

Table 1. Infested kernel average recognition rates listed by insect size and insect species.^[a]

Larvae Size	Infested Kernels Detected ^[b]		
	Lesser Grain Borer	Rice Weevil	Average
Large	7.9 (1.4)	8.6 (1.1)	8.3 (1.3)
Medium	7.1 (1.6)	7.7 (1.2)	7.4 (1.4)
Small	5.5 (1.5)	6.3 (1.5)	5.9 (1.6)
Average	6.8 (1.8)	7.5 (1.6)	7.2 (1.7)

^[a] Data listed are from the 0.46-mm roller gap tests only. Recognition rates listed are the average from 100-g samples with a total of 10 infested kernels. Both HRW and SRW results are averaged together for this table.

^[b] Standard deviations in parenthesis.

Table 2. Infested kernel average recognition rates listed by wheat class and insect species.^[a]

Wheat Class	Infested Kernels Detected ^[b]		
	Lesser Grain Borer	Rice Weevil	Average
HRW	6.7 (1.7)	7.4 (1.7)	7.1 (1.7)
SRW	6.9 (1.9)	7.6 (1.5)	7.3 (1.7)
Average	6.8 (1.8)	7.5 (1.6)	7.2 (1.7)

^[a] Data listed are from the 0.46-mm roller gap tests only. Recognition rates listed are the average from 100-g samples with a total of 10 infested kernels. All insect sizes are pooled together in this table.

^[b] Standard deviations in parenthesis.

Table 3. Infested kernel average recognition rates listed by wheat moisture content and insect species.^[a]

Wheat Moisture	Infested Kernels Detected ^[b]		
	Lesser Grain Borer	Rice Weevil	Average
11%	7.0 (1.8)	7.6 (1.6)	7.3 (1.7)
13%	6.6 (1.8)	7.4 (1.6)	7.0 (1.7)
Average	6.8 (1.8)	7.5 (1.6)	7.2 (1.7)

^[a] Data listed are from the 0.46-mm roller gap tests only. Recognition rates listed are the average from 100-g samples with a total of 10 infested kernels. All insect sizes are pooled together in this table.

^[b] Standard deviations in parenthesis.

average recognition rate for large-sized rice weevil and lesser grain borers combined was 8.2 out of 10 infested kernels. In contrast, the average recognition for small larvae was 5.9 out of 10 infestations. While the effect of insect size is certainly substantial, none of the means were significantly different at the 95% confidence level as determined by Tukeys means comparison test.

In the secondary tests where only one rice weevil infested kernel was mixed with 50 g of noninfested wheat, 96% of the kernels containing large larvae were detected and 78% of the kernels with medium-sized larvae were detected. In contrast, from the main tests where 10 infested kernels were mixed with 100-g HRW at 11% moisture, the average recognition rate was 86% for samples having large larvae rice weevils and 77% for samples containing medium-sized rice weevils.

These results suggest that during the main test with 10 infested kernels per 100 g, up to 10% of infested kernels were not recognized because two or more infested kernels were being crushed in the mill at the same time. The problem of two infested kernels appears to be more prevalent when two large larvae are crushed at the same time compared with two medium-sized larvae. This could be caused by less insect

fluid being released by the smaller larvae. The results also indicate that as the incidence of insect infestations decrease, the recognition rate should increase by as much as 5% to 10%. Higher accuracy is needed at low levels of infestation rather than high infestation levels.

Aside from two infested kernels being crushed at the same time, another likely cause for undetected infestations could be incomplete crushing of the kernel, which prevented the insect fluid from short-circuiting the mill rolls. A smaller mill gap may improve detection rates but it would also require a larger motor and cause more wear on the machine. In these experiments, the motor load was 7.4 to 7.8 amps while crushing HRW wheat at the 0.46-mm gap. Since the motor was rated for a maximum of 8.3 amps, smaller gaps could not be studied at this time. Lower throughput rates or lower insect infestation rates should see an increase in detection accuracy, as there would be fewer insect-infested kernels being milled at the same time.

Wheat class and moisture content had a small but noticeable effect on recognition rates (tables 2 and 3). SRW wheat had slightly higher recognition rates than HRW wheat. This may be due to the more gradual breakage of SRW kernels when compared with HRW kernels. Recognition rates were also slightly higher for bulk moisture of 11% compared with 13%. On average, recognition dropped by less than 4% as moisture increased from 11% to 13%. Higher moisture caused a smaller difference between the minimum of each dip and the background signal, resulting in detection of fewer infested kernels.

The voltage drop across the mill rolls was somewhat affected by the size of the infesting insect. As shown in table 4, the average minimum voltage dip caused by infested kernels was lower for rice weevils than for lesser grain borers. For each insect species, the voltage drop across the rolls increased as larvae size increased. This is probably caused by more fluid being released from larger larvae, therefore increasing the conductance between the mill rolls.

The gap size between the mill rolls had a substantial effect on recognition rates. Only rice weevils were used in the large (0.71-mm) gap tests. Table 5 displays the recognition rates for the two different gap sizes. On average, the recognition rates decreased 16%, from 7.4/10 to 6.2/10, by going from the small roll gap to the large gap. The recognition rate decrease was most severe for the small larvae, where large gap recognition decreased by 31% over recognition achieved with the smaller gap. As the kernels are compressed and larval fluid was released, its contact with one or both mill rolls caused the conductivity between the rolls to increase.

Table 4. Average minimum voltage caused by insect-infested kernels listed by insect species and larvae size.

Larvae Size ^[a]	Minimum Voltage (V) of Dip Caused by Infested Kernel ^[b]		
	Lesser Grain Borer	Rice Weevil	Average
Large	2.2 (0.3)	1.4 (0.2)	1.8 (0.5)
Medium	2.4 (0.3)	1.7 (0.3)	2.1 (0.5)
Small	2.8 (0.5)	2.4 (0.5)	2.6 (0.5)
Average	2.5 (0.5)	1.8 (0.6)	2.2 (0.6)

^[a] Note that larger insects caused voltages to drop lower. Data are from the 0.46-mm roller gap test only.

^[b] Standard deviations are in parenthesis.

Table 5. Infested kernel recognition rates for kernels infested by rice weevils and the mill rolls set at the small (0.46-mm) and large (0.71-mm) gap.

Larvae Size	Infested Kernels Detected ^[a]		
	Wider Gap (0.71 mm)	Small Gap (0.46 mm)	Average
Large	7.4 (1.3)	8.7 (1.2)	8.0 (1.4)
Medium	7.1 (1.6)	7.6 (1.3)	7.3 (1.5)
Small	4.2 (1.6)	6.1 (1.3)	5.1 (1.7)
Average	6.2 (2.1)	7.4 (1.6)	6.8 (2.0)

^[a] Recognition rates listed are the average from 100-g samples with a total of 10 infested kernels.

The larger gap reduced the amount of fluid that could have contacted both rolls, thus reducing recognition rates.

Analysis of variance (ANOVA) was performed to model recognition rates using the following independent variable: roller gap, insect species, insect size, wheat class, and moisture content. The ANOVA found that only moisture content was not a significant factor to the model. Insect size was the most significant variable, closely followed by roller gap size.

Control Samples

For the 47 control samples, the average minimum gradient was -0.048 V, with a standard deviation of 0.018 V. The range of minimum values was from -0.02 to -0.09 V. A Shapiro-Wilk W test for normality (Shapiro and Wilk, 1965) of the minimum gradient data suggested that these data were normally distributed. Thus, it was expected that 99.7% of all samples with no insect infestations would have had a minimum gradient above -0.1 V. The gradient threshold of -0.3 for the detection of infested kernels was three times higher than the background signal. A lower threshold could have possibly been used if there was no concern of excessively high moisture kernels being introduced into the sample (discussed later).

Effect of High Moisture Kernels

Tests where high moisture (15% to 17%) kernels were added to common moisture level grain (11% to 13%) showed that the wet kernels did cause dips in the conductance signal;

however, the slope of these dips was lower than those caused by the infested kernels. As such, occasional wet kernels should not cause false positive counts for the insect-infested grain. Figure 6 shows a conductance signal and gradient for a sample of grain at 13% moisture with the addition of 10 kernels at 17% moisture. When comparing the dips in the raw signal shown in figure 6 with those in figure 3 for dips caused by insects, it is evident that the high moisture kernels did not drop nearly as sharply as those from insect infested kernels. From the 26 samples, comprising 260 wet kernels, only one was counted as an insect-damaged kernel using the signal analysis program developed for detecting infested kernels. The one false positive was from a sample of HRW wheat at 13% moisture spiked with 17% kernels. The gradient exceeded the threshold when two high moisture kernels were crushed at the same time. In figure 6, the dip occurring at approximately 5.9 s was due to two 17% moisture kernels being crushed at the same time. The corresponding gradient with this dip is -0.29, just under the threshold for counting the dip as an infested kernel.

Having such high moisture kernels would be a rare occurrence for grain coming out of storage or off a covered truck or rail car. Once the grain has been stored for over 24 h, the moisture content of that single seed would be close to the equilibrium moisture of the bulk of wheat (Hoseney, 1986). When these tests were re-run after holding the high moisture kernels with the normal moisture wheat for 24 h, the dips that were seen in figure 6 did not appear.

Comparison with X-Ray Imaging Methods for Detecting Infested Kernels

Classification results obtained from the roller mill system data compare favorably with previous studies where X-ray images for detecting insect-infested kernels were used. Human examination of X-ray films has a higher detection rate of infested kernels at all maturity levels but can have false-positive errors of 1.0% or higher (Haff, 2001). Furthermore, inspecting X-rays is tedious, time-consuming, and requires the use of expensive X-ray equipment. Computer algorithms that automatically scan X-ray images may have recognition rates of over 90% for insect-infested kernels but have higher false-positive rates, at about 7.4%

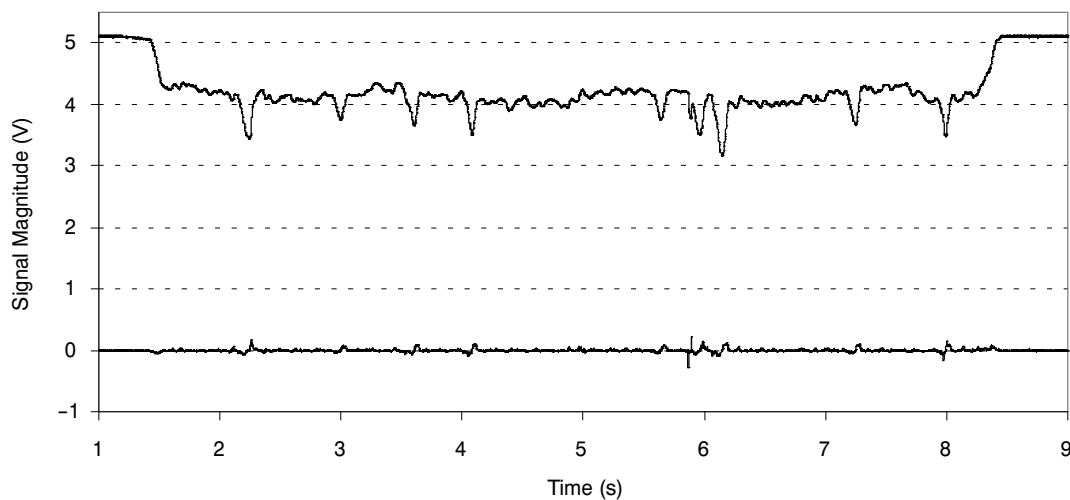


Figure 6. Raw voltage signal (top) and gradient signal (bottom) for a HRW sample at 13% moisture mixed with 10 HRW kernels at 17% moisture. Note that the slopes of the dips in conductance due to the high moisture kernels are not as steep as those from insect infested kernels (fig. 3).

(Haff, 2001). X-ray imaging methods have the advantage of being nondestructive and can detect kernels where an immature insect died before emerging and has dried out. In contrast, throughput of the roller mill is approximately 30,000 kernels/minute and has nearly negligible false-positive rates without the need for elaborate calibrations or subjective interpretation of results. Thus, the roller mill system may be more suitable for use in grain receiving stations.

CONCLUSION

A laboratory roller mill was fabricated to mill and record the electrical conductance of wheat and infested wheat kernels. An insect-infested wheat kernel causes an abrupt change in conductance that can be used to estimate the number of infested kernels in a sample. In this study, over 300 tests, using 100-g samples with ten infested kernels, were conducted in the experimental mill. Recognition rates ranged from 8.2 out of 10 infested kernels with large rice weevil larvae to 5.5 out of 10 small lesser grain borer larvae. The mill required less than 10 s to crush 100-g samples and would require approximately one minute to process a kg sample. The system can be set up to automatically estimate insect infestation levels by using the simple signal processing algorithm presented in this study.

This system is very affordable, as parts for the entire system cost less than \$1500. The system can be used wherever grain needs to be inspected for live insect infestations, such as grain receiving facilities for flour mills and loading docks for overseas shipments, and can also help determine fumigation requirements of stored grain.

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REFERENCES

- ASABE Standards. 2006. S352.2. Moisture measurement - Unground grain and seeds. St. Joseph, Mich.: ASABE.
- Christensen, C. M., and R. A. Meronuck. 1986. *Quality Maintenance in Stored Grains and Seeds*, Chap. 3. Minneapolis, Minn.: University of Minnesota Press.
- Becker, K. 2002. Personal communication. ConAgra Foods, Omaha Nebr.
- Dowell, F. E., J. E. Throne, and J. E. Baker. 1998. Automated nondestructive detection of internal insect infestation of wheat kernels by using near-infrared reflectance spectroscopy. *J. Econ. Entomology* 91(4): 899-904.
- Federal Grain Inspection Service (FGIS). 1997. *Book II: Grain Grading Procedures*, Chap. 13. Washington, D.C.: USDA-GIPSA-FGIS.
- Fornal, J., Jelinski, T., Sadowska, S. Grundas, J. Nawrot, A. Niewiada, J. R. Warchalewski, and W. Baszczak. 2007. Detection of granary weevil *Sitophilus granarius* (L.) eggs and internal stages in wheat grain using soft X-ray and image analysis. *J. Stored Prod Res.* 43(2): 142-148.
- Haff, R. P. 2001. X-ray inspection of wheat for granary weevils. Ph.D. diss. Davis, Calif.: University of California, Davis.
- Hagstrum, D. W., K. W. Vick, and J. C. Webb. 1990. Acoustical monitoring of *Rhyzopertha dominica* (Coleoptera: Bostrichidae) populations in stored wheat. *J. Econ. Entomology* 83(2): 625-628.
- Hoseney, R. C. 1986. In *Principles of Cereal Science and Technology*, Chap. 6. St. Paul, Minn.: American Association of Cereal Chemists.
- Karunakaran, C., D. S. Jayas, and N. D. White. 2004. Detection of internal wheat seed infestation by *Rhyzopertha dominica* using X-ray imaging. *J. Stored Prod. Res.* 40(5): 507-516.
- Milner, M., D. L. Barney, and J. A. Shellenberger. 1950. Use of selective fluorescent stains to detect insect egg plugs on grain kernels. *Science* 112(29 December 1950): 791-792.
- Pearson, T. C., D. L. Brabec, and C. R. Schwartz. 2003. Automated detection of internal insect infestations in whole wheat kernels using a Perten SKCS 4100. *Applied Engineering in Agriculture* 19(6): 727-733.
- Shapiro, S. S., and M. B. Wilk. 1965. An analysis of variance test for normality. *Biometrika* 52(3/4): 591-611.
- Sharifi, S., and R. B. Mills. 1971. Developmental activities and behavior of the rice weevil inside wheat kernels. *J. Econ. Entom.* 64(5): 1114-1118.
- Storey, C. L., D. B. Sauer, O. Ecker, and D. W. Fulk. 1982. Insect infestations in wheat and corn exported from the United States. *J. Econ. Entomology* 75(5): 827-832.

