Acoustic Properties of Soybeans

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Abstract

Acoustic transmission and impact force response methods were investigated for classification of soybeans. The transmission method was slow and not suitable for real-time application. A polynomial was fitted to the deconvolved frequency spectrum of acoustic impulse data for soybeans. The curve fitting procedure successfully predicted the mass of each soybean. The size of soybeans was related to the bandwidth. Diseased soybeans consistently showed narrower bandwidths than healthy soybeans. The diseased and damaged soybeans had broad variations in low frequency which was quantifiable by threshholding the error of fit in the curve fitting procedure.

Introduction

The acoustic properties of a soybean refer to the transmittance, absorption, or reflection of sound waves by the soybean. Any changes, even very small ones, in the structure or health of the seed changes it's acoustic properties. These properties and, more specifically, changes in these properties can be quantitatively evaluated by analyzing the frequency components of the sound wave.

The objective of this research* was to develop an acoustic frequency analysis technique for characterizing various physical properties of soybeans related to marketing quality. Interfaced with a microcomputer system, the acoustic signals generated by seeds and grains can provide a continuous, on-line quality control method during post-harvest operations.

Frequency-domain analysis is a powerful technique for analyzing waves over the whole frequency range from subsonic to sonic. The analysis also is the most sophisticated in terms of required skills and equipment. Analytical procedures such as Fast Fourier Transforms (FFT) can be performed on-line to identify the ways in which selected frequencies can be absorbed, transmitted and reflected by the soybean. Such frequency responses can be correlated with various physical properties of soybean that are related to quality.

Two types of acoustic methods were investigated during the research. These methods were: acoustic transmission and impact force response.

In acoustic transmission, a kernel is placed between "input" and "receiving" transducers where the former introduces an acoustic impulse to the kernel and the latter records the wave transmitted through the kernel. Both waves, the input and the transmitted, can be digitally recorded and analyzed by a Fast Fourier Transform. The two spectra can then be compared, usually by dividing the transmitted wave by the input wave to identify frequencies that are preferentially absorbed by the kernel which can be an indicator of kernel quality.

In the impact-force method, a kernel is dropped on an acoustic transducer, and the impact generates a mild impulse wave both in the transducer and in the kernel. The nature of this wave is very sensitive to the properties of the kernel. By correlating the detail features of the wave with various properties of the kernel, a powerful method for probing the quality of kernel can be developed.

Herrenstein and Brusewitz (1985) measured the sound pressure level for wheat using a microphone and related the pressure level to frequency, grain flow rate, grain moisture content, and distance between microphone and wheat. Finney, Jr. et al. (1968) evaluated firmness of bananas using a sonic technique. Seymour and Hamann (1984) designed a microcomputer based acoustic system to study the crispness of potato chips. Delwiche et al. (1987a) analyzed the impact forces of peaches and found the impact force characteristics highly correlated with firmness and poorly correlated with mass and radius. Delwiche et al. (1987b) developed a sorter to separate peaches based on firmness. Rohrbach et al. (1982) modeled the rebounding force of blueberries and correlated the peak force with mass and firmness. Nahir et al. (1986) analyzed the impact force response of tomatoes and suggested solutions to a mathematic model. The proposed solution was well correlated with sorting performance. No study dealing with impact force analysis for soybeans was found in the literature. Also, no literature was found dealing with acoustic transmission for any agricultural products.

Sound Wave Transmission Through Soybeans

The instrumentation assembled for the dynamic frequency analysis of acoustic waves transmitted by soybeans consisted of two contact transducers, an ultrasonic pulser, a LSI 11/04 minicomputer system with analog to digital conversion, a video terminal, a hard copy

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device and disk drive peripherals. The programming software for data acquisition and mathematical computation was written in Fortran. The basis for mathematical computation is the Fast Fourier Transform.

A single kernel of soybean was placed between two piezoelectric P-wave transducers. One of the transducers was pulsed with a sharp voltage spike, which launched a broadband acoustic pulse into the seed. The second transducer received the pulse after it had passed through the seed.

A variety of different couplants was evaluated during preliminary experiments to insure proper contact between soybean and the transducers. These couplants were: silicone (grease and caulk), gelatin, clay, a variety of rubber, and direct coupling. Gelatin provided consistent signals and therefore was used as the couplant. Soybeans were placed in two different orientations between the transducers: one, where the long axis of the soybean was horizontal and, the other where the long axis of the soybean was vertical. The latter orientation was chosen for all subsequent tests because the signals were stronger, and it was easier to hold the soybean between the transducers.

The time-domain signal for the transmittance wave for a "good" soybean (determined visually) is shown in figure 1. The transmitted wave was analyzed into its frequency components through an FFT to yield a graph that depicted the relative magnitude of the various harmonics in the original signal. The display was in the "frequency domain" and showed the characteristic spectrum of a good soybean (fig. 2). It was a reference against which any other soybean could be compared.

The same information was obtained for a kernel of poor quality (a shriveled seed by visual examination) and the time domain signal is shown in figure 3 and its FFT in figure 4.

The FFT for the two soybeans, good quality and poor quality, were then compared in the frequency domain by dividing the frequency spectrum of the bad kernel by the reference spectrum from the good kernel. The result is shown in figure 5, which highlights the differences between the acoustic transmission of the two kernels. Valleys represent frequencies present in the transmission through the good seed and absorbed by the kernel of poor quality. Likewise, peaks represent frequencies that were transmitted by the bad kernel.

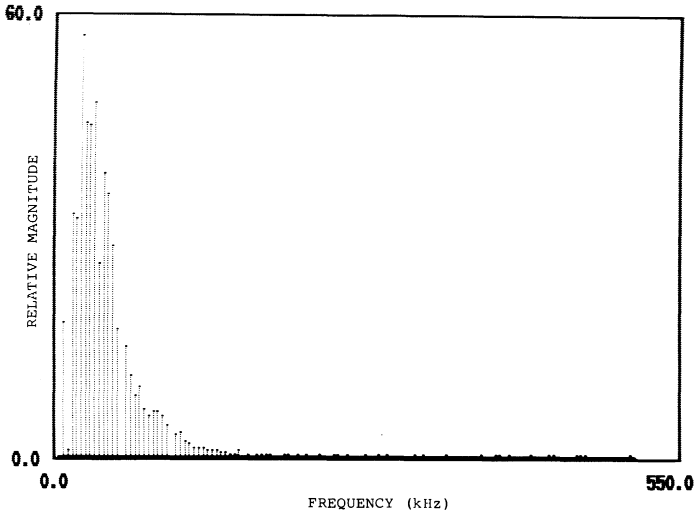

Figure 2–Frequency spectrum for the good soybean.

The relative absorption spectrum was smoothed and the significant features were the positions of the two peaks and the valley (fig. 5). These results indicated that it is feasible to acquire and analyze the acoustic transmission data of soybeans and that differences between kernels of good and poor quality can be observed.

A number of soybeans from various soybean seedlots were obtained and each soybean was subjected to the acoustic transmission test. The acoustic transmission features varied from soybean to soybean but the spectrum was very hard to describe in any mathematical manner. So, there was no way of correlating the transmission spectra with the size or mass of soybeans. Additionally, the placement of each soybean between the transducers required some time, and the process was slow. Therefore, an alternate acoustic technique (impact-force response) was investigated to detect the quality of soybeans.

Impact-Force Response

The experimental set-up to drop soybeans onto a piezoelectric force transducer is shown in figure 6. Soybeans, in this setup, were placed in the v-trough of a

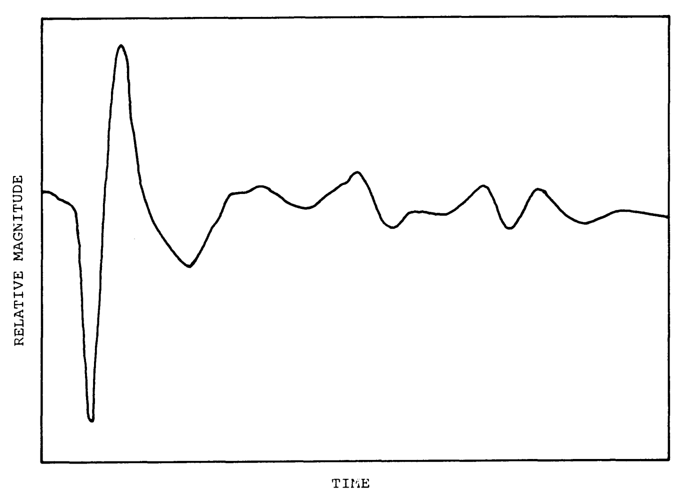

Figure 1–Transmittance wave for a good soybean.

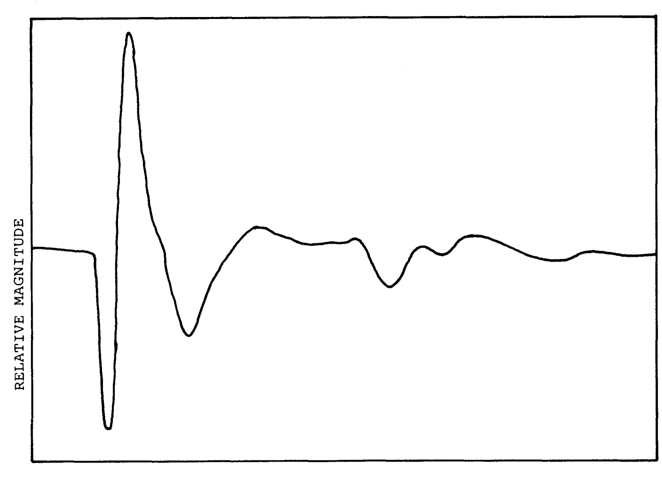

Figure 3–Transmittance wave for a shrivelled soybean.

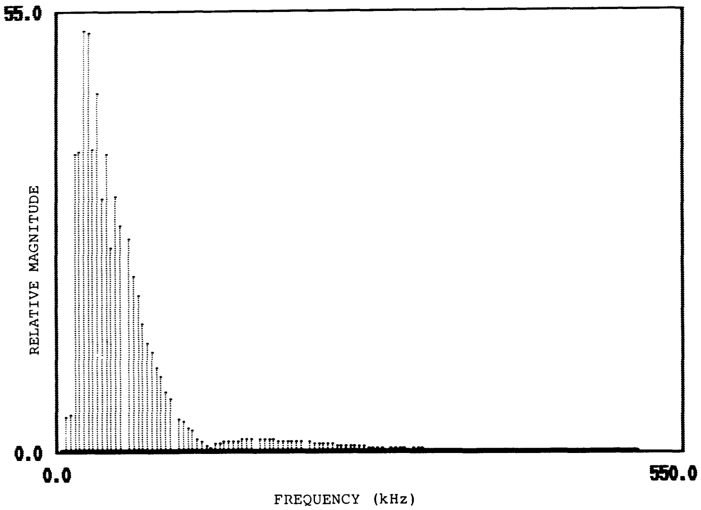

Figure 4–Frequency spectrum for a shrivelled soybean.

vibratory feeder and dropped through a guide tube on the force transducer. The speed of the vibratory feeder was adjusted so that the soybeans slide in the trough (as opposed to rolling) to maintain the orientation before the drop. The impact signal (millivolts) from the transducer was routed to a digitizer and then to a computer. The digitizer was a high-speed analog to digital converter capable of running at 200,000 samples/second. It also stored the resulting data in the internal memory and processed the data into a format useful for the computer.

During preliminary testing with this system, nylon balls 4.76 mm in diameter and weighing 0.05 gm were dropped on the transducer to test the repeatability of the signals produced by the system. Excellent repeatability of the waveform was obtained.

DECONVOLUTION TECHNIQUE

Figure 7 shows the time and frequency spectra of two soybeans. To correlate the frequency spectra with the quality parameters, each spectrum must be mathematically described. The shapes of the frequency spectra (fig. 7), however, are so complex that they are not described in terms of mathematical functions which makes it hard to draw any quantitative conclusions from the data. Fortunately, the small nylon beads chosen to calibrate the system and evaluate its repeatability turned out to have many dynamic features in common with the soybeans. This revealed that many of the features in the spectra were actually properties of the measuring system, not of the soybeans. To offset these problems, an operation known as "deconvolution" (Proakis and Manolakis, 1988) was applied. With the nylon beads as reference sources (because of their consistency), the dependence of the recorded signals on the measuring system was cancelled out.

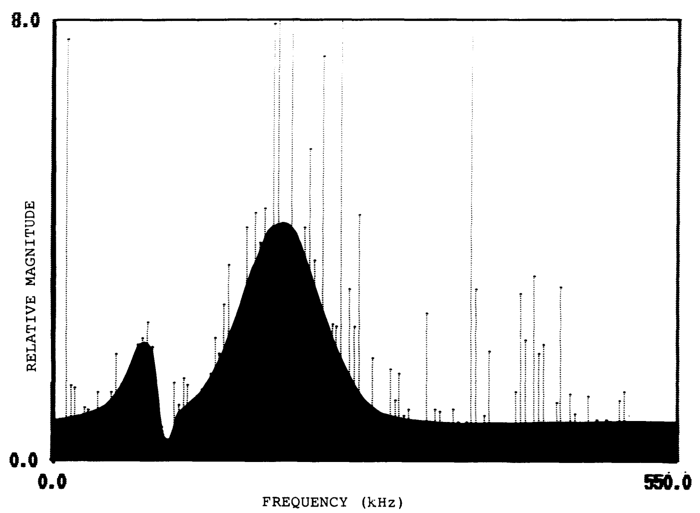

Figure 5–Relative absorption spectrum (with the smoothed plot superimposed).

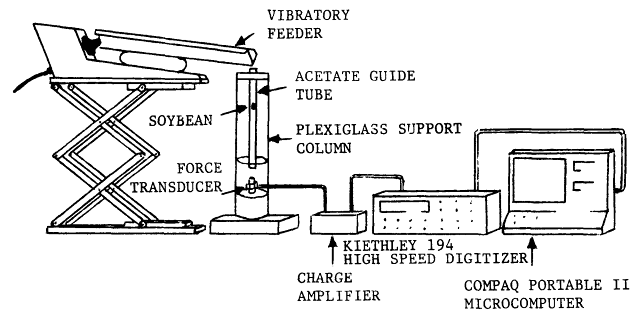

Figure 6–Schematic layout of impact-force test equipment.

Figure 8 shows the deconvolved spectrum after the transducer characteristics have been removed from the Fourier Transform. Note the broad and smooth characteristic (curves that are sketched in) with other significant features (e.g., the stack-like deviation between 13 kHz and 23 kHz on the lower trace) and some noise superimposed. Ignoring the superimposed behavior for now, we find that the bandwidth of the major characteristic changes with the size of the bean. This can be measured quantitatively by locating the point at which the curve crosses its own half-maximum power level. The half-power level for both these curves has been drawn on the graph as a horizontal line. At the point where each of the sketched-in curves crosses the horizontal line, a vertical line has been dropped to the axis, revealing that the bean of 19R (i.e., 19/64 of an inch in diameter) "rolls off" between 15 kHz and 20 kHz while the 15R bean rolls off between 25 kHz and 30 kHz. This pattern has been shown to be

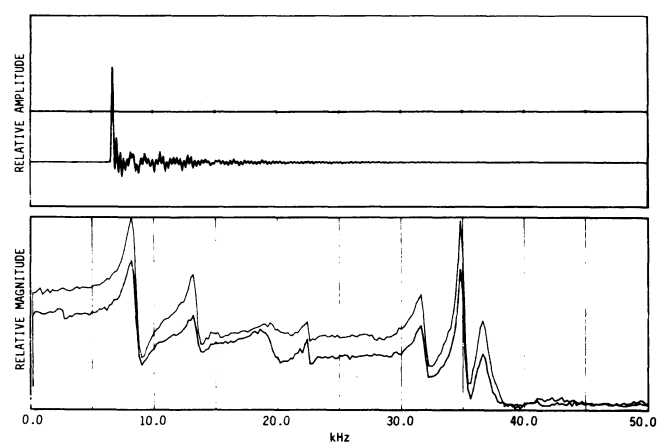

Figure 7–Time domain plot (top) and frequency domain plot (bottom) for acoustic data from two soybeans.

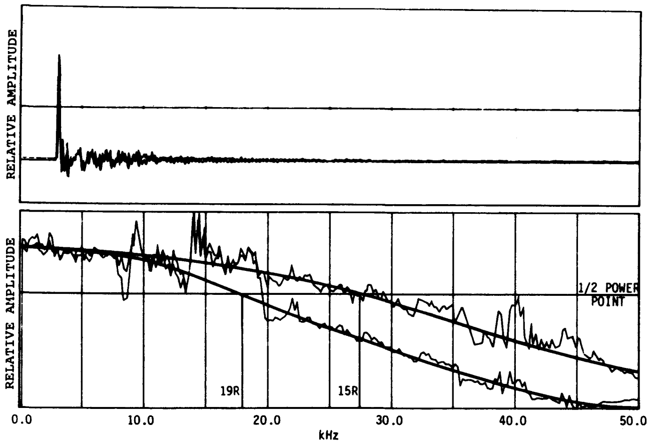

Figure 8–Deconvolved spectrum and effect of soybean size on acoustic data.

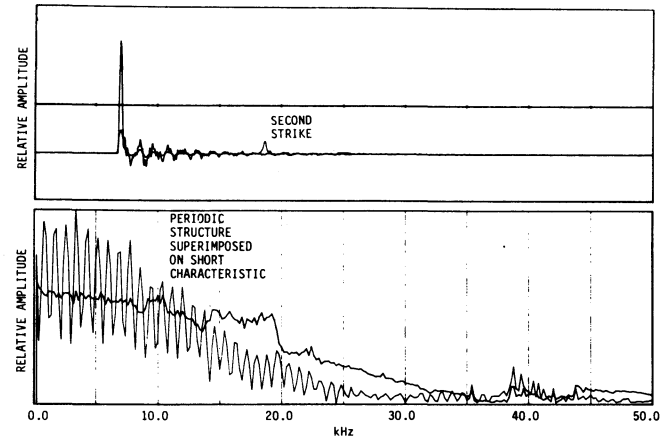

Figure 10–Effect of surface characteristics (shriveled or mechanically damaged) of soybeans on acoustic data.

consistent over a number of trials, indicating an inverse relationship between seed size and strike bandwidth.

Figure 9 compares a healthy and a diseased soybean of different sizes. Because they do not peak at the same level on the graph, each has been given its own "half-power" level. The good bean is in the size range from 14R to 16R (14/64 of an inch to 16/64 of an inch in diameter). From previous studies with other healthy beans, we would expect it to "roll off" between 23 kHz and 30 kHz; in fact, it rolls off near 23 kHz leading us to believe that it probably is a 16R bean. Studies with healthy beans would cause us to anticipate the bad bean, which is under 14R, to "roll off" above 27 kHz, but in fact, it "rolls off" well below 15 kHz. This is a characteristic that showed up among diseased beans about 80% of the time. It varied from test to test, leading us to believe that it is sensitive to the orientation of the bean on impact, but it almost never occurs among beans previously classified as healthy. This gives us one possible discriminator for healthy vs. unhealthy beans. If we have a prior crude estimate of the size of the beans, then any bean showing a bandwidth significantly narrower than expected may be rejected as diseased. More to the point, a count of the number of beans that "fall short" may be used to estimate the percentage of diseased beans in a stream.

Some diseased or damaged beans have rough or gnarled surfaces. These kernels show themselves by striking the transducer twice within a very short time (of the order of milliseconds). The time-domain signal (upper portion) of figure 10 shows this behavior. The effect of double-strike on the frequency spectrum is shown in the lower portions of figure 10 (note the periodic ringing in low frequencies). Despite the "double strike," a smooth curve through the diseased trace still "rolls off" around 13 kHz to 15 kHz.

Other diseased beans show an abnormal rise on the strike characteristic in the time domain (fig. 11). This effect produces an abnormal "double peak characteristic" in the frequency domain, which is likely caused by a loosening of the outer hull of the bean from the body of bean. A second, very narrow characteristic in the low frequency range is superimposed on the normal behavior. Again, We note that the normal characteristic (bandwidth) rolls off earlier for the bad bean than for the good bean. This roll-off may even have been overestimated (moved to the right) because of the presence of the abnormal peak.

Curve Fitting Routine

The deconvolution process revealed visual trends with physical quality parameters of soybeans. The next logical step was to develop a mathematical description of the data so that the spectrum could be quantitatively parameterized quickly and accurately. An empirical approach was employed to accomplish this task.

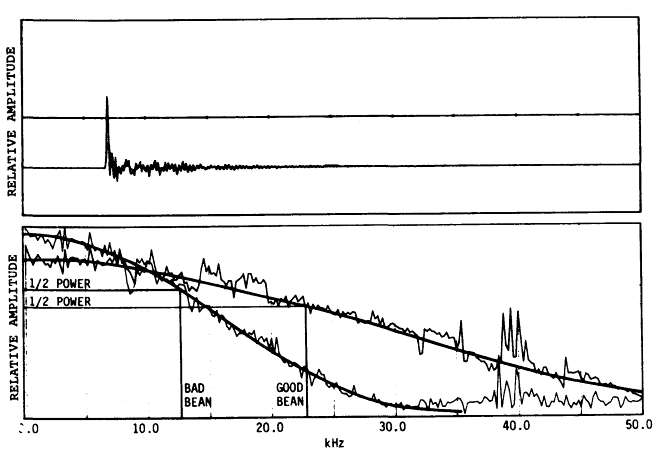

Figure 9–Effect of soybean quality (healthy vs. diseased) on acoustic data.

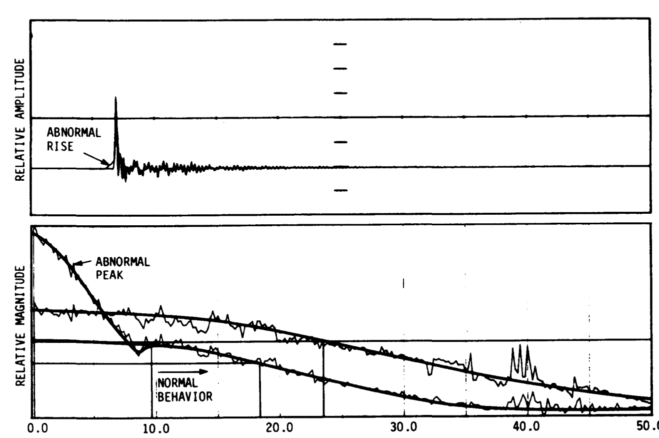

Figure 11–Abnormal acoustic behavior of some unhealthy soybeans.

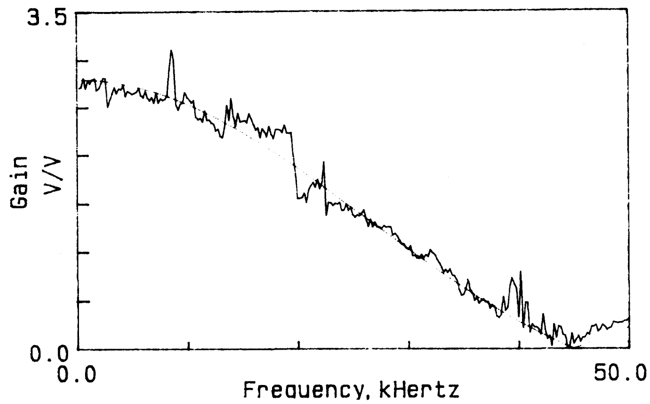

Figure 12–An overlay of the curve from dual-Gaussian procedure on the deconvolved spectrum of soybean acoustic data.

In developing an empirical approach, a number of mathematical expressions were attempted, including the polynomial approximations, rational polynomials, sine functions and simple Bessel functions. A dual-Gaussian function with a time delay was finally chosen as the best empirical approach, which is expressed as:

$$F(\omega) = [A e^{-(\omega/\alpha)^2} - B e^{-(\omega/\beta)^2}] e^{jwt} \qquad (1)$$

where
- w = frequency in radians/sec,
- j = square root of the negative one,
- e = radix base of the natural logarithm,
- A, α, B, β and t are constants.

In the above expression, A and B are the sizes of the two Gaussians, α and β are the widths of the Gaussians, and t is the time delay constant.

A FORTRAN program was written to solve for the parameters using an iterative least-square method. Figure 12 shows the deconvolved frequency spectrum of a soybean with a curve fitted to the data from the dual-Gaussian function.

TAYLOR SERIES APPROXIMATION

The mathematical expression for fitting a Taylor series to a set of data is as follows:

$$F(x) = C_0 + C_1 X + C_2 X^2 + C_3 X^3 + C_4 X^4 + \cdots \qquad (1)$$

The dual Gaussian fit used earlier revealed that the function was symmetric, and consequently, the odd terms drop out. Furthermore, terms beyond fourth power of X did not significantly improve the function and the resultant expression is

$$F(x) = C_0 + C_2 X^2 + C_4 X^4 \qquad (2)$$

Let H1 $= C_0 = a_0$
H2 $= C_2/C_0 = a_1/a_0$
H3 $= C_4/C_0 = a_2/a_0$

where, H1, H2, and H3 are related to seed quality parameters.

Let any soybean quality parameter (say mass denoted by M) be given by the linear model of H1, H2, H3, and the cross products. So,

$$M = K_0 + K_1H_1 + K_2H_2 + K_3H_3 + K_4H_1H_2 + K_5H_1H_3 + K_6H_2H_3 + K_7H_1H_2H_3 \qquad (3)$$

$$= K_0 + K_1a_0 + K_2a_1/a_0 + K_3a_2/a_0 + K_4a_1 + K_5a_2 + K_6(a_1a_2)/a_0^2 + K_7(a_1a_2)/a_0 \qquad (4)$$

$$= K_0 + K_1a_0 + K_4a_1 + K_5a_2 + K_2\,a_1/a_0 + K_3\,a_2/a_0 + K_7(a_1a_2)/a_0 + K_6(a_1a_2)/a_0^2 \qquad (5)$$

$$= c_0 + c_1a_0 + c_2a_1 + c_3a_2 + c_4\,a_1/a_0 + c_5\,a_2/a_0 + c_6(a_1a_2)/a_0 + c_7(a_1a_2)/a_0^2 \qquad (6)$$

For a number of values of M, equation 6 can be written in matrix form as follows:

$$\begin{bmatrix} M_1 \\ M_2 \\ M_3 \\ \bullet \\ \bullet \\ M_n \end{bmatrix} = \begin{bmatrix} 1 & a_{10} & a_{11} & \bullet & \bullet & (a_{11}a_{12}/a_{10}^2) \\ 1 & a_{20} & a_{21} & \bullet & \bullet & (a_{21}a_{22}/a_{20}^2) \\ 1 & a_{30} & a_{31} & \bullet & \bullet & (a_{31}a_{32}/a_{31}^2) \\ \bullet & \bullet & \bullet & \bullet & \bullet & \bullet \\ \bullet & \bullet & \bullet & \bullet & \bullet & \bullet \\ 1 & a_{n0} & a_{n1} & & & (a_{n1}a_{n2}/a_{n0}^2) \end{bmatrix} \begin{bmatrix} c_0 \\ c_1 \\ c_2 \\ \bullet \\ \bullet \\ c_7 \end{bmatrix}$$

The dual-Gaussian curve fitting procedure took 30-60 seconds for each soybean which is too slow for any practical purpose. Attempts were therefore made to search for a curve-fitting routine that will be faster and still accurate. The polynomial fit from Taylor Series approximation provided this alternative.

If n = 8, the coefficients c_0 .... c_7 can be determined from the above simultaneous algebraic equations. If n > 8, the solution is overdeterminant. For calibration purpose, it is necessary to drop a number of soybeans and n > 8. Therefore, the values of coefficients c_0 .... c_7 should be such that,

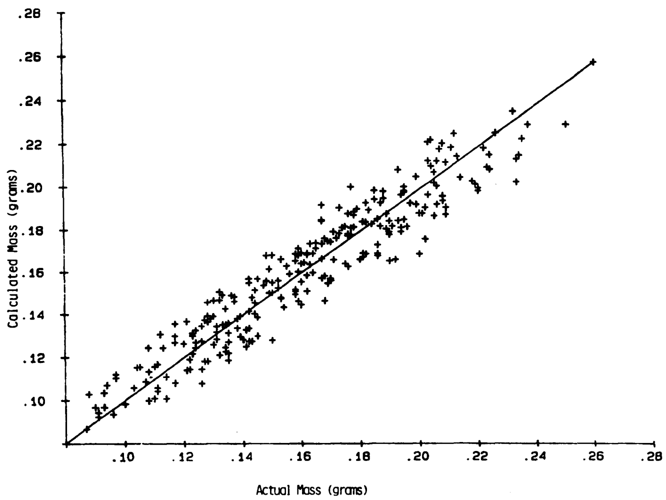

Figure 13–Plot of actual mass with calculated mass.

$$\Sigma_{i=1} (M_i - M_{ip})^2 = \text{minimum} \quad (7)$$

where

M_i = actual values of mass of soybeans,

M_{ip} = predicted values of mass of soybeans.

A subroutine program was written in ASYST software to solve for the coefficients. A number of soybeans from various seedlots were obtained and the mass of each soybean was recorded by a precision electronic balance. These soybeans were dropped on the transducer by placing them in the vibratory feeder by hand and the polynomial curve fitting procedure was performed. Excellent predictions of mass were obtained with a standard error of 6.6% (fig. 13).

Damage and Disease Identification

Soybeans that were damaged or diseased had distinguished characteristics in the time-domain and the frequency-domain spectra. A shrivelled soybean for example produced a double strike in the time domain (fig. 10), and the corresponding frequency spectrum showed broad variation in low frequencies. Contrasting visually the time-domain signal for the shriveled seed with that of a good soybean is simple. However, quantitative expression of such deviant strike is necessary if the technique is to be applicable in a real production environment. Calculation of the fit in the curve fitting procedure provided this discriminator. The error of fit is defined as:

$$E^2 = \frac{\Sigma_i (Y_i - f(X_i))^2}{\Sigma_i f(X_i)^2} \quad (8)$$

where,

E^2 = error of fit,

Y_i = actual value,

$f_{(Xi)}$ = values from the fitted polynomial.

The healthy soybeans consistently provided low error of fit (below 10%), and the diseased or damaged soybeans had a relatively large error. By thresholding the error of fit, the diseased and damaged soybean were identifiable. The error of fit criterion, by itself, was not always successful. At times, the polynomial fitted the acoustic data for the diseased and damaged seeds well. Therefore, a combination of mass estimation and error of fit was used to discriminate the diseased and damaged soybeans. A soybean that is a split, for example, may provide little error of fit in the polynomial, but is still rejected as of poor quality because of the low mass estimation.

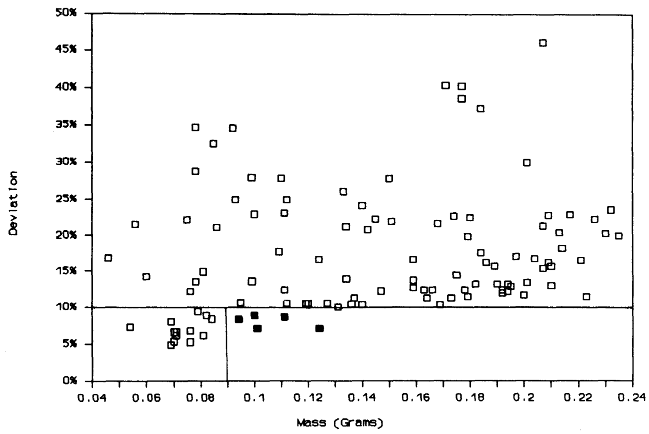

Figure 14–Scatter plot of error of fit and mass for damaged or diseased soybeans.

Figure 14 shows the plot of mass and error of fit for a number of soybeans that were diseased or damaged. If the error of fit is used as the single criterion and a value of 10% or above is considered to indicate poor quality, 83% of the soybeans in figure 14 would have been properly classified as bad seeds. By threshholding either the mass below 0.09 grams or the error of fit above 10%, 95% of the diseased and damage seeds would be properly classified as bad seeds (5% would be misclassified as good soybeans which are shown in dark squares in figure 14).

Summary and Conclusions

Appropriate instrumentation was assembled to collect acoustic transmission data for soybeans and software was written for frequency analysis of the data. Although the transmission study clearly demonstrated that acoustic discrimination of soybeans was feasible, the technique was slow and not suitable for an actual production environment. The impact-force method was then investigated and showed real promise for characterization of soybean quality. A dual-Gaussian curve was fit to the deconvolved frequency spectrum of acoustic impulse data for soybeans. Soybean size was inversely proportional to bandwidth. The diseased soybeans consistently showed a much narrower bandwidth than the healthy seed. A soybean with wrinkled surface usually struck the transducer twice within a few milliseconds that was observed in the frequency spectrum. The diseased and damaged soybeans had broad variations in low frequencies which were quantifiable by thresholding the error of fit in the curve fitting procedure. The curve-fitting procedure also successfully predicted the mass of each soybean from the acoustic frequency data.

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