DEVELOPING AND IMPLEMENTING A PROCEDURE
TO DETERMINE THE RELATIONSHIP
BETWEEN MOISTURE CONTENT AND
ACOUSTIC PROPERTIES OF
FLOWING WHEAT

By

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DEVELOPING AND IMPLEMENTING A PROCEDURE TO DETERMINE THE RELATIONSHIP BETWEEN MOISTURE CONTENT AND ACOUSTIC PROPERTIES OF FLOWING WHEAT

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PREFACE

The purpose of this study was to develop a procedure for determining the relationship between moisture content and acoustic properties of flowing wheat. By using the developed method, select parameters were to be identified and quantified to gain a general understanding of the relationship, and to help direct future research.

The author wishes to express sincere appreciation to Dr. Gerald H. Brusewitz for his advice, criticism, encouragement and patience throughout the course of this study. Appreciation is also extended to Dr. Glenn A. Kranzler, Dr. Marvin L. Stone, and Dr. Richard L. Lowery, members of the advisory committee, for guidance and critical review. Appreciation is given to Bruce Lambert, Mark Appleman, and other members of the Agricultural Engineering Laboratory.

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CHAPTER I

INTRODUCTION

Determining the moisture content of cereal grains is done in many different ways. The ASAE standard method for measuring moisture content in wheat is to dry wheat in a convection oven at a temperature of 130 degrees celsius for nineteen hours (ASAE, 1984). The time and equipment required for this method have spurned interest in developing other methods for measuring moisture content quicker and more conveniently. Several methods used for measuring moisture content include desiccant drying, distillation methods, chemical methods, gas chromatography, electrical methods, and nuclear methods (Henry, 1975). Most of these methods do not lend themselves to a relatively low cost, accurate, and fast moisture content reading.

High speed, mechanized handling of cereal grains has led to more timely and accurate information requirements for moisture content. Knowledge of grain quality for harvesting equipment and in grain storage bins requires an instantaneous method of measuring the moisture content of grain on a continuous basis. The accurate and timely sensing of moisture content on harvesting equipment will allow for compensation in forward speed and harvester adjustments. Sensing may even indicate whether harvesting should continue and identify areas of the field which are ready for harvest. The grain trade industry has become more aware of the importance of moisture content in their handling, drying, and marketing decisions. The need for a fast and accurate method of measuring moisture content on a continuous basis will continue to increase in the grain handling industry (Krutz, 1982).

This study was initiated by the idea that wheat with different moisture contents sounded differently when impacting an object. The physical structure of the wheat kernel along with the elastic and vibrational properties of the wheat kernel are dependent on the moisture content. The fundamental frequencies change at different moisture levels (Mohsenin, 1970).

Wheat impacting another surface produces sound from the wheat as well as sound from the impacted surface. To correctly measure only the sound of the wheat, the sound from the impacted surface must be isolated either by the microphone or by proper data analysis. Sensing only wheat impacting other wheat kernels and eliminating sound from unwanted sources was considered the most direct approach for this study. The non-uniformities of the wheat kernel moisture distribution within the kernel and foreign material led to the evaluation of a stream of wheat. Using or considering a stream of wheat allows for an averaging of different possible wheat collisions as well as debris or broken kernel collisions. A stream of wheat also allows for a better representation of the true moisture content of the wheat with a larger sample. With the use of computers, moisture variation can be measured in addition to average moisture.

This study was a broad look at the sound amplitude produced at different frequencies by flowing grain as affected by moisture content. Without any previous experience on the subject, many assumptions and arbitrary decisions were made before and during this study. Variables such as grain type, wheat variety, type of microphone, distance of falling wheat, diameter of wheat pile, etc... were selected for consideration using intuition and preliminary experimentation. Hopefully, the results of this study will show the potential of this method for measuring moisture content and provide information for the direction of further research and development.

The objectives of this project were to;

1) Develop a procedure for determining the relationship between moisture content and acoustic properties of flowing wheat.

2) To measure the characteristics of the sound generated by wheat falling on wheat and to relate moisture content of the wheat to those characteristics.

CHAPTER II

LITERATURE REVIEW

Sound is defined as an oscillation in pressure, stress, particle displacement, particle velocity, etc., in an elastic or viscous medium. Most frequently sound is associated with pressure oscillations in a fluid medium. Sound pressure is the total instantaneous pressure at a given point, in the presence of a sound wave, minus the static pressure at that point. In general terms, sound pressure is identified as

$$Ps = F / S \tag{1}$$

where:

Ps = sound pressure
F = force due to sound acting on a surface
S = surface area

Sound pressure, as a measurand for a transducer, is expressed in terms of sound pressure level. (SPL) is typically expressed in units of decibels. SPL is defined as 20 times the logarithmic ratio of the mean sound pressure to a mean-square reference pressure. It is normally expressed in decibels as 20 times the logarithm to the base 10 of the ratio of the rms sound pressure to an rms reference pressure. The reference pressure is usually taken as 2 X 10 E-4 dynes/ cm E+2.

$$SPL = 20 \log (p(rms) / p\ ref(rms)) \qquad (2)$$

Sound pressure level is an attempt to approximate a measure of loudness of pure tones as perceived by the human ear. A standard method of measuring sound level uses a sound-level meter consisting of a microphone, an amplifier, standard weighting networks, a graduated attenuator, and an output-indicating meter. The weighting networks referred to as A, B, and C are used to denote commonly accepted standard frequency-response characteristics of the instrument. Octave band pass filters are often used on sound-level meters to isolate particular frequency bands.

Sound pressure levels are affected by the environment surrounding a sound emitting source. A free sound field is a sound field in a homogenous medium free of any acoustically reflecting boundaries. Free-field frequency response of a sound-pressure measuring transducer is the ratio, as a function of frequency, of the output of the transducer in a sound field to the free-field sound pressure that would exist at the transducer location in the absence of the transducer. Pressure frequency response is the ratio, as a function of frequency, of the output to sound pressure which is equal in phase and amplitude over the entire sensing-element surface of a sound-pressure measuring transducer (Norton,1969).

Sonic methods have been used to determine the firmness of fruits and vegetables. Abbott and Bachman (1968) describe a method of measuring firmness in fruits and vegetables using sonic energy applied to the whole fruit or vegetable, resulting in determination of a series of resonance frequencies. These resonance frequencies are used along with the mass of the fruit or vegetable to determine a "stiffness coefficient" that measures the stiffness or firmness of the fruit or vegetable. Abbott and Bachman (1968) further state that the frequency of the resonance vibration depends on the size, shape, and texture of the product. The larger the size and the softer the texture, the lower will be the pitch. Resonance can frequently be analyzed in terms of the configuration and elastic properties of the resonating body.

A method of measuring the firmness of soft fruits as presented by Nybom (1962) involves recording the ability of the fruits to transmit vibrations. The method works on the principle that fruit firmness is related to its ability to conduct vibrations. A very soft fruit will tend to significantly dampen the propagated vibrations. Higher frequencies may be more efficient in discriminating between soft and firm fruits.

Research work has been done to investigate corn breakage as related to moisture content. Herum and Blaisdell (1981) reveal that higher moisture content corn absorbs more energy before fracturing than lower moisture content corn. Chowdhury and Buchele (1979) showed that peak shearing force on corn kernels is inversely proportional to kernal moisture content. Results showed that as moisture content increased to 25 % and higher, the breakage rate went to zero. Small changes in moisture content in the 15 % moisture content range corresponded with large differences in breakage susceptability. At lower moisture contents it was deduced that moisture is present in multiple layers and consequently has lower displacement mobility.

A microcomputer-based instrument for measuring the crispness of food products was devised and tested by Seymour and Hamann (1984). The system consisted of a spectrum analyzer and an Apple II+ microcomputer used to analyze acoustical frequencies in the 0.5 to 3.3 khz range. The system used the spectrum analyzer to obtain accurate digital real time frequency information in graphic form and the computer to store and reduce the data. The study relied on the supposition that most of the pertinent information would be in the low frequency range and low cost instrumentation could be used for the research.

CHAPTER III

MATERIALS AND EXPERIMENTAL EQUIPMENT

Wheat used for this study was hard red winter wheat which had been harvested the previous summer and stored in sealed 20 liter drums at 5 degrees C. The wheat was not trashy, and it was determined that it did not need to be cleaned.

Wheat samples were adjusted to desired moisture content levels and kept in plastic 5 liter containers. The containers were sealed to prevent moisture change and stored at 5 degrees C to prevent spoilage.

For the purpose of this study, moisture contents of the lowest and highest moisture levels of wheat expected in stored or harvested wheat were selected as limits. Using moisture levels between these limits provided for better assessment of trends and correlations. The high limit was arbitrarily set at about 19 percent[1] and the low limit at about 10 percent. Three equally spaced moisture levels were selected between these limits. Moisture levels for the different groups were obtained by adding water, mixing, and letting the moisture content stabilize for three days. The

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[1] All moisture contents were computed on a wet basis

higher moisture levels were obtained by adding water several times to obtain the desired moisture levels. Wheat samples were kept in a refrigerator at 5 degrees C in sealed five liter containers to maintain moisture levels and to prevent spoilage until ready for experimentation.

Approximate moisture levels were obtained using a Burrows model 700 digital moisture computer. Precise moisture readings were taken at the time of the experiment. A sample was taken from each moisture content level and reduced to a 100 gram sample by weighing on a Sartorius type 2254 top loading balance and placed in small rectangular aluminum trays. Each group of five samples was placed in an oven at a temperature of 130 degrees C for a time period of 19 hours according to the ASAE standard method for determining moisture content in wheat. The weight readings before and after drying in the oven were subtracted to obtain moisture content wet basis for each sample.

Structure

The wheat was temporarily stored during tests in a sheet metal bin with a height of 1.21 meters and a cross sectional area at the top of 0.41 meters by 0.20 meters. The bin had these same cross sectional dimensions 0.86 meters down to where the bin tapered at a 45 degree angle on the sides to dimensions of 0.21 meters by 0.20 meters. The bin extended 0.25 meters to the base. (Figure 1) The base of the bin was slotted for two sheets of metal; one sheet

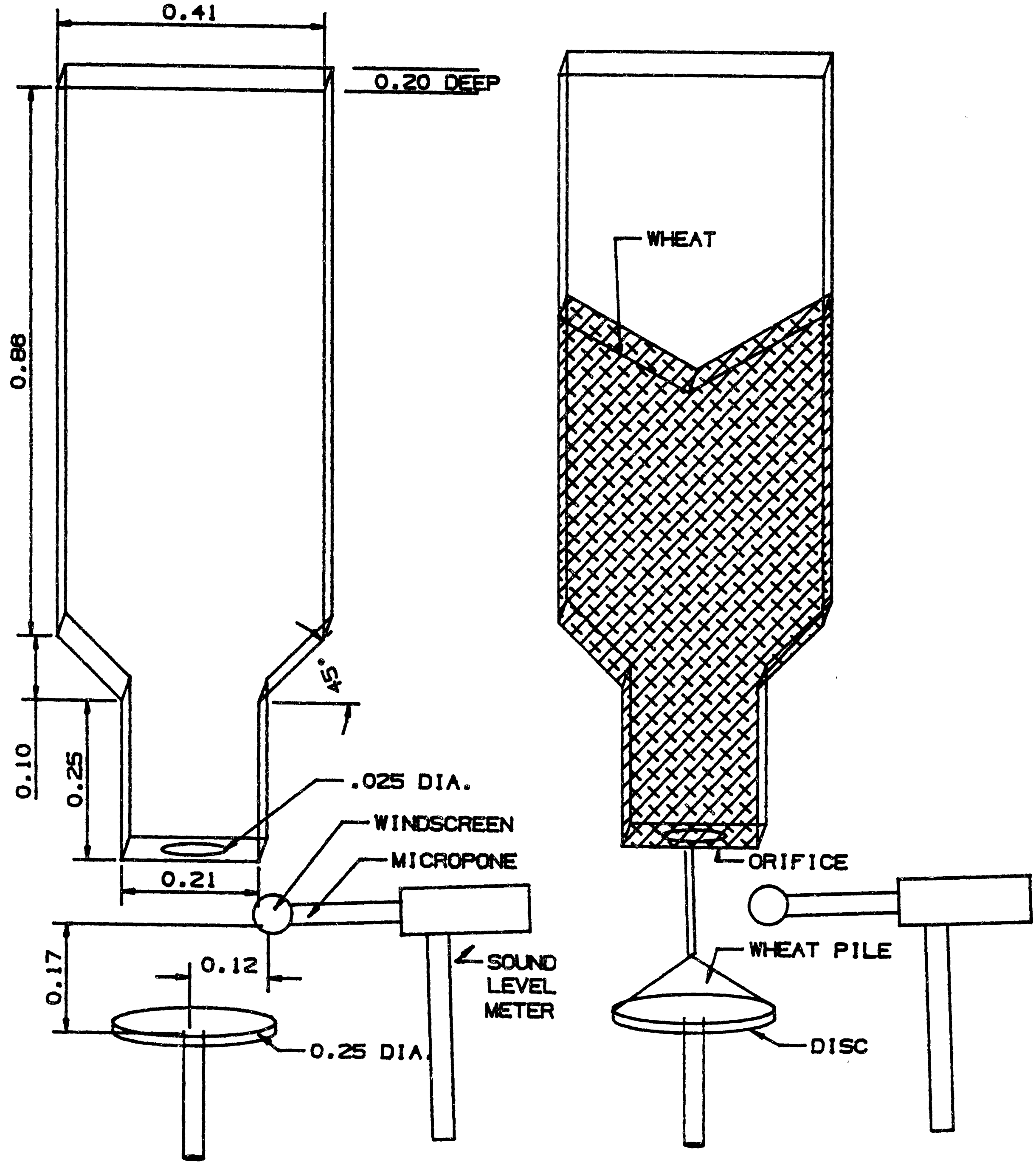


Figure 1. Drawing of experimental wheat bin and microphone

to start and stop grain flow and the other sheet with an orifice in the center for the desired grain flow. The orifice size needed to be small to minimize the need for a large bin size and to provide run times sufficiently long to obtain representative samples. The orifice needed to be sufficiently large to keep moisture content from affecting volumetric flow rate. Information from moisture content studies with corn and wheat was used to select an appropriate orifice size. A 2.5 cm orifice satisfied the above requirements, and the volumetric flow rate did not vary significantly at different moisture contents. (Table I)

The bin had a 0.025 meter by 0.300 meter hole near the top of the front of the bin for filling the bin with grain. A sheet metal piece extended several centimeters towards the front of the bin at a 45 degree angle for pouring grain into the bin.

The bin was supported in a rectangular frame made of lightweight angle iron. The bin was supported at the front and back by the frame at the top and bottom and at four corners by adjustable legs to allow for leveling.

The wheat dropped from the bin onto a 25 cm circular steel plate that was centered 26.5 cm below the orifice. The plate was covered with hard rubber 0.0063 meters thick and foam rubber 0.0126 meters thick to absorb sound caused by the wheat contacting the plate. The wheat was collected beneath the circular plate into a catch pan lined with the foam rubber to dampen noise from the wheat contacting the

TABLE I

VOLUMETRIC FLOW RATE OF WHEAT THROUGH 2.5 CM ORIFICE

MOISTURE CONTENT (%)	VOLUME (ML)	TIME TO EMPTY BIN (SECONDS)	VOLUMETRIC FLOW RATE (ML/SEC.)
10.0	3200	35.0	91.4
10.0	3200	33.8	94.7
14.3	3200	33.5	95.5
14.3	3200	34.6	92.5
17.9	3200	36.9	86.7
17.9	3200	37.6	85.1

surfaces.

Sound level meter

A model 2204 Bruel & Kjaer impulse precision sound level meter was used for capturing the wheat sound. The sound level meter was equipped with a model 1613 frequency band filter. A Bruel & Kjaer model 4220 pistonphone was used to calibrate the meter.

A 3 meter extension cable model # A00027 was connected from the meter to the microphone assembly to allow for positioning flexibility. The microphone assembly was securely clamped to the test frame around a piece of rubber to dampen any structural vibrations.

A 2.5 cm Bruel & Kjaer pressure response microphone model # 4145 supplied with the sound level meter was used for preliminary experimentation. Results showed that there was a need to measure the sound readings above the high end of the frequency response curve for this microphone. A 1.25 cm Bruel & Kjaer pressure response microphone model # 4134 was used because it had a wider frequency response region. The high end of the frequency response for the 1.25 cm microphone was of more value for the grain sounds and the higher low end eliminated some of the dominant low frequency room noise present in the laboratory without sacrificing any useful information. The 4134 microphone had a frequency range of 5 hz. - 20 khz. +/- 2 decibels with an approximate dynamic range of 32 - 153 decibels. (Figure 2)

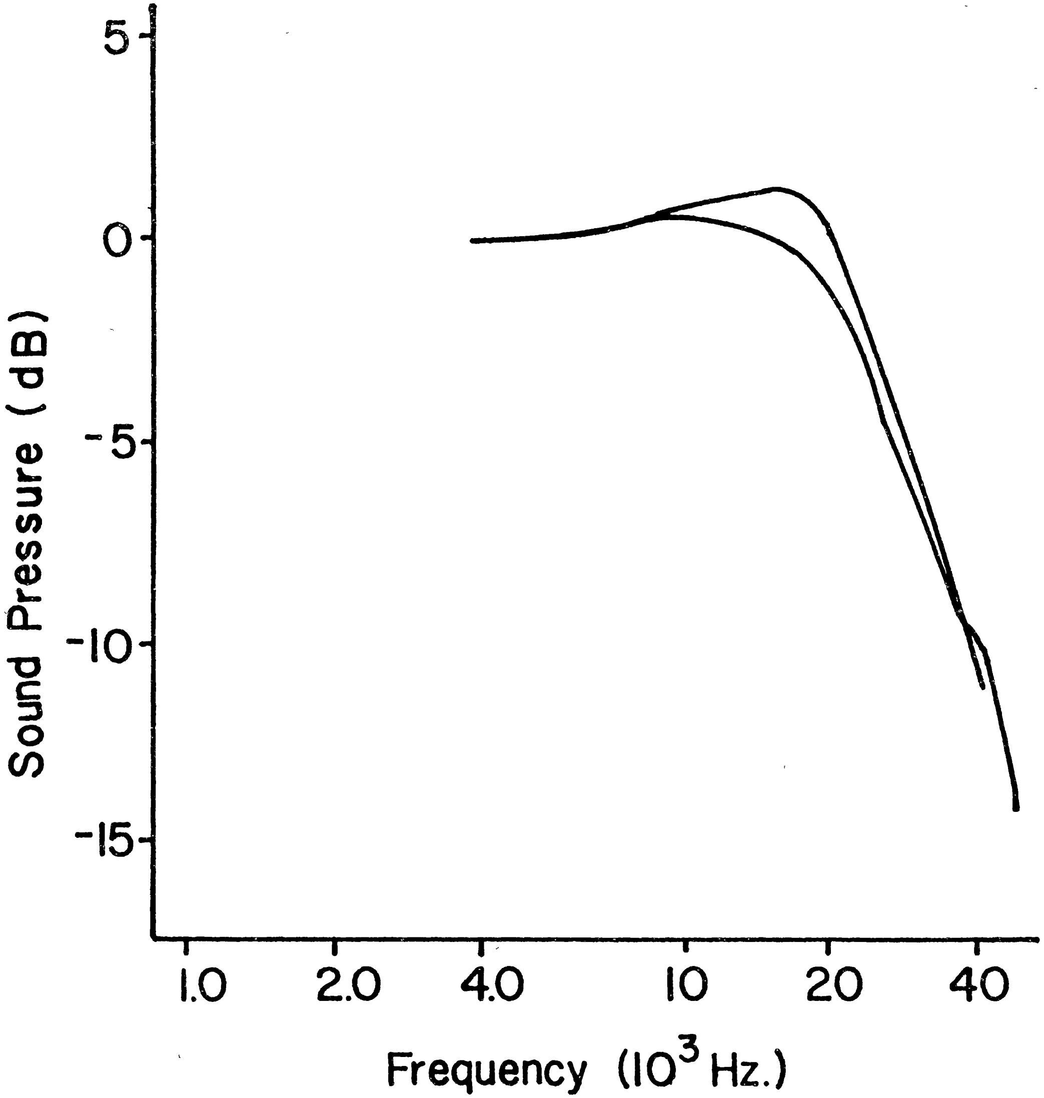


Figure 2. Bruel & Kjaer model # 4134 microphone frequency response curve

A pressure response microphone was used instead of a free field response microphone because of availability. Due to the high strength of the wheat impact signal and the close direct positioning of the microphone, the use of a pressure response microphone was determined to be adequate for this experiment. The microphone was protected from air movement and dust with a sponge rubber windscreen.

The sound level readings were taken from the sound level meter using an electrical cable connected to the output jack. The output jack on the meter supplied an analog output proportional to the meter reading on the display. To obtain the correct output reading the analog output was added to the sensitivity level setting.

Spectrum analyzer

A Hewlett-Packard model 3580A spectrum analyzer was used to analyze the sound signal from the Bruel and Kjaer sound level meter. The spectrum analyzer is a low frequency instrument that has been optimized for use in the 5 Hz to 50 kHz range. Specific frequency bands can be analyzed within this 50 kilohertz range. The spectrum analyzer had features including digitally stored display, adaptive sweep, selectable bandwidths, 30 nV sensitivity and 80 decibel dynamic range.

The unit was was recently calibrated at the factory. The spectrum analyzer was equipped with X and Y analog output jacks having an output of 0 volts at the bottom of the scale and a linear increase to 5 volts at the top of the scale. Two electrical cables connected these jacks to two channels on an analog-to-digital conversion board.

Data Manipulation

The analog-to-digital converter used was a Interactive Structures model AI 13A 16 input, 12 bit, A-D converter. The board resolved the total range into 4096 parts for the two channels used. This converter was used in an Apple II computer.

An Apple II computer with a 16K language card was used to massage the data from the spectrum analyzer and to store the results on diskette. The computer was equipped with two Apple disk drives and a Zenith monochrome monitor. This system was used to capture data from the analog-to-digital converter and store in memory. Raw data were analyzed and stored on floppy diskettes. Data from the diskettes were transferred to the Oklahoma State University IBM mainframe computer for further data analysis using a Racal-Vadic 300 baud phone modem and a VISITERM software communication package. The statistical package used to evaluate the data was Statistical Analysis System (SAS User's Guide, 1982).

CHAPTER IV

DEVELOPMENT OF METHODOLOGY

A Latin Square statistical design was used to minimize the effect of factors such as drying of wheat samples, battery strength in the sound meter, background noise variations, and operator fatigue. The three treatments evaluated (Table II) were moisture content level, the time period needed for five replications, and the sequence in which the moisture levels were tested within each time period. The experimental design was used to determine if the time periods needed for five replications, and the sequence in which the moisture levels were tested, had any significant effect on the results. The design was set up as a Latin Square design to minimize any time related variability effects that might be present on the moisture content effect. Assuming the sequence and time period effects were negligible, then analyzing five replications for each moisture content level help show the repeatability in the moisture measuring process and support the conclusions.

In preparation for each run the bin was loaded with the appropriate five liter sample of wheat. Each run was started by removing the stop plate at the bin orifice and

TABLE II

EXPERIMENTAL STATISTICAL DESIGN

	REP 1	REP 2	REP 3	REP 4	REP 5
TIME 1	MC 1	MC 2	MC 3	MC 4	MC 5
TIME 2	MC 5	MC 1	MC 2	MC 3	MC 4
TIME 3	MC 4	MC 5	MC 1	MC 2	MC 3
TIME 4	MC 3	MC 4	MC 5	MC 1	MC 2
TIME 5	MC 2	MC 3	MC 4	MC 5	MC 1

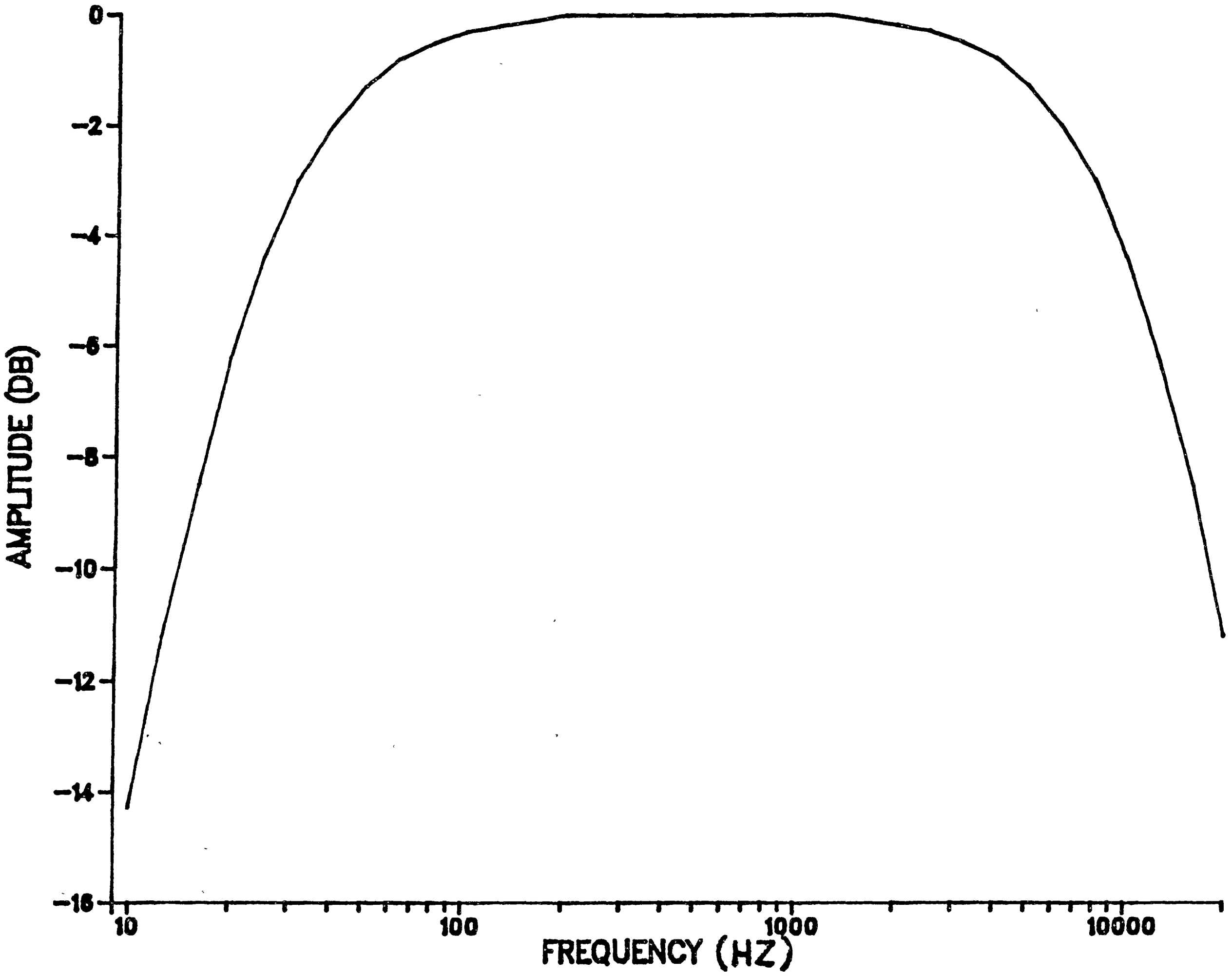
* MC = MOISTURE CONTENT

allowing for wheat flow. Before any measurements were taken, grain was allowed to flow for 15-20 seconds to allow for stabilization of the wheat flow and the sound patterns. Data samples were run using the order specified in the experimental design. After a block of five samples had been tested, the sample groups were measured for moisture content.

Sound readings for a wheat sample were conditioned by the Bruel & Kjaer sound level meter. The sound meter was operated in the linear mode without the available octave band filters. The "C" weighted filter was used to help eliminate background noise present in the frequency range below 1000 Hz. Most of the prominent background noise present in the laboratory was caused by the air handling system and was eliminated by the "C" weighted filter. Figure 3 shows the relative response curve for the "C" weighted filter used.

The sensitivity for the sound meter was set at 60 dB. Preliminary work showed that the average linear response was in the low 60 dB range for all moisture content readings. The 60 dB setting was best for the range of moisture contents to insure maximum sensitivity without exceeding the operating range. The sound level meter was operated in the fast mode to prevent averaging any quick changes in amplitude or frequency response.

The analog output from the sound meter ranged from 0 volts rms at minimum meter deflection of -10 dB to 5 volts



Source: Beranek, Noise and Vibration Control (1971)

Figure 3. Relative response curve for C-weighting

rms at maximum meter deflection of +10 dB. The analog output from the sound level meter was transmitted by a cable to the spectrum analyzer for frequency analysis.

The spectrum analyzer was operated at an input sensitivity level of + 10 dB. This was the minimum sensitivity level that could be used with the 0 to 5 volt rms input and still allow for the 7 plus volt peak voltage encountered. The amplitude mode was set to the 10 dB log setting. This setting provided for 10 dB per division on the amplitude or Y scale with 10 divisions present. The resolution bandwidth was set at the 300 Hz position. The frequency resolution at this setting was more than adequate, and the higher bandwidth allowed for a broader frequency bandwidth and slower sweep times.

The spectrum analyzer allowed for isolating certain frequency ranges from 0 to 50 kHz. Zero kHz was initially chosen as the low end of the frequency range. Because of background noise and the lack of wheat sound observed below the 5 kHz range, some of the lower frequency information obtained was not used. The upper frequency limit was determined by setting the frequency span per division adjustment at 5 kHz per division. The ten divisions along the frequency or X scale set the upper frequency at 50 kHz.

The smoothing function for the spectrum analyzer was operated in the maximum smoothing position. The smoothing done with the analyzer helped to eliminate gross peaks and valleys in the frequency analysis curve displayed on the

CRT. The sweep time per division setting was operated at 5 seconds per division. With 10 divisions this provided a 50 second sound analysis for each sample.

Data from the spectrum analyzer were transmitted to an analog to digital converter through X and Y channels. The spectrum analyzer had an analog output from 0-5 volts rms at maximum deflection for the X and Y scales. The 0-5 volt output was compatible with the Interactive Structures analog to digital converter. Maximum resolution of both channels on the analog to digital converter was 4096 points with the 0-5 volt input range. The analog to digital converter sampled the spectrum analyzer's voltage level for each channel at a rate of once every 0.029 seconds.

A BASIC program was written on the Apple II computer to read the level of both channels on the analog to digital board and store these points in memory. The BASIC program checked both channel levels and stored the values in consecutive X and Y arrays until the X level reached a 5 volt level indicating a sweep had been completed. The BASIC program was compiled using an "Einstein" compiler to increase the efficiency of the program and to increase subsequent sampling rates by a factor of five.

Exceedingly large upward and downward movements in the frequency analysis curve were apparent in the transformation from an analog to a digital representation. The smoothing function on the spectrum analyzer worked only on the screen output of the spectrum analyzer and not on the analog output. The data stored in memory was smoothed three times using a simple smoothing algorithm before storing the information to disk. The points were smoothed by taking the average of the point before, the point, and the point after. This method was used for all points except the first and last points. The algorithm smoothed the first point by taking the average of the first and second points and smoothed the last point by taking the average of the last point and the previous point. The formulae used were;

$$X1_{SM} = (X1 + X2) / 2 \qquad (3)$$

where:
$X1_{SM}$ = X1 smoothed

$$X(i)_{SM} = (X(i-1) + X(i) + X(i+1)) / 3 \qquad (4)$$

with $i = 2$ to $n-1$

$$Xn_{SM} = (X(n-1) + Xn) / 2 \qquad (5)$$

The digital representation of the data collected was graphically displayed by the BASIC program after smoothing to assure the data appeared correct. The algorithm used to smooth the data seemed to have about the same effect as the smoothing function of the spectrum analyzer.

The equipment settings and the sample number were entered for each sample using an information screen written into the program. After all the appropriate information was entered for the sample (Table III), the information and the data were written to a sequential text file under a file name composed of the sample number. All samples were stored on diskette in this manner for later data analysis. The text file for each sample stored an average of 1700 frequency and corresponding amplitude points. (See Appendix C for program screens and program listing)

Twenty-five data sets with approximately 3400 points were stored on the data diskettes. Evaluation and analysis of this data was sufficiently extensive to warrant using the OSU IBM main frame computer with the VISITERM communications program and a Racal-Vadic phone modem. The data was sent to the IBM using the Apple II computer to read and send the particular sequential text file.

The data for each sample was composed of 1700 frequency and corresponding amplitude pairs of data points. Frequency data ranged from 0-50 kHz along the X axis. The representation of the frequency range was recorded from the analog to digital board as a data point from 0-4096. A zero data point represented a frequency reading of zero kHz while a 4096 data point represented a 50 kHz frequency. The resolution along the X scale was computed to be 4096/50 kHz or 81.92 data points per kHz. This resolution appeared to be more than adequate for the experiment.

The corresponding amplitude reading for each frequency was recorded as 4096 for a point at the bottom of the scale to zero for a point at the top of the amplitude scale. The

TABLE III

DATA STORAGE INFORMATION

N - NUMBER OF POINTS
SN - SAMPLE NUMBER
LF - LOWER FREQUENCY
HF - HIGHER FREQUENCY
RB - RESOLUTION BANDWIDTH
SM - SMOOTHING LEVEL
SW - SWEEP TIME / DIVISION
SE - SOUND LEVEL METER SENSITIVITY
FL - FILTER TYPE
SC - AMPLITUDE MODE
MC - MOISTURE CONTENT
IS - INPUT SENSITIVITY

resolution for the Y or amplitude axis calculated to be 4096 points/100 dB or 40.96 data points per 1 dB. Again, this resolution appeared to be more than adequate for the experiment.

The frequency readings for each sample were converted from digital form to corresponding frequency by multiplying each digital point by 50/4096 to obtain the data in kHz. The conversion of the amplitude readings was more complicated, since the digital amplitude reading recorded was relative to the actual signal amplitude for maximum deflection. Full scale amplitude readings with the equipment settings used was determined to be approximately 81 dB on a scale range of 100 dB. Converting digital amplitude data to corresponding amplitude readings in dB required substituting the digital data into the equation:

$$\text{dB reading} = \frac{(4096 - \text{digital reading})}{40.96} - (100 - 81) \qquad (6)$$

The converted data were stored in amplitude (dB) versus frequency (kHz) form in new data files on the IBM main frame computer for statistical analysis.

CHAPTER V

RESULTS

Moisture

The moisture contents of the twenty-five sample groups are listed in Table IV. As desired, the five different moisture groups were fairly evenly spaced throughout the range of 11 to 19 percent (Table V). The results of the moisture readings indicate that the moisture groups were very close in moisture content.

A typical graph of frequency versus amplitude for a particular moisture content is depicted in Figure 4. The amplitude is greatest in the 10 kHz range and decreases fairly linearly to the 50 kHz range. The amplitude versus frequency curves for different moisture levels show that the curves have the same shape, with the curves being shifted upward as the moisture level decreases.

Modeling Response Curves

An attempt was made to explain the amplitude versus frequency relationship by mathematically modeling the response curves. The frequency range interpreted was from 5 kHz to 50 kHz with readings taken every 12.2 Hz. The

TABLE IV

OVEN DETERMINED MOISTURE CONTENTS

REPLICATION	MOISTURE GROUP	ORIGINAL WEIGHT (GRAMS)	FINAL WEIGHT (GRAMS)	MOISTURE CONTENT (%)
1	A	100.00	89.00	11.00
1	B	100.00	86.27	13.73
1	C	100.00	84.71	15.29
1	D	100.00	82.30	17.70
1	E	100.00	81.05	18.95
2	A	100.00	88.98	11.02
2	B	100.00	86.23	13.77
2	C	100.00	84.69	15.31
2	D	100.00	82.23	17.77
2	E	100.00	81.16	18.84
3	A	100.00	88.90	11.10
3	B	100.00	86.30	13.70
3	C	100.00	84.75	15.25
3	D	100.00	82.26	17.74
3	E	100.00	81.12	18.88
4	A	100.00	88.98	11.02
4	B	100.00	86.20	13.80
4	C	100.00	84.76	15.24
4	D	100.00	82.33	17.67
4	E	100.00	81.34	18.66
5	A	100.00	88.98	11.02
5	B	100.00	86.30	13.70
5	C	100.00	84.76	15.24
5	D	100.00	82.34	17.66
5	E	100.00	81.14	18.86

TABLE V

VARIABLILITY OF MOISTURE GROUPS

MOISTURE GROUP	MOISTURE CONTENT AVERAGE (%)	MOISTURE CONTENT STANDARD DEVIATION (%)
A	11.032	0.039
B	13.740	0.044
C	15.266	0.032
D	17.708	0.047
E	18.838	0.108

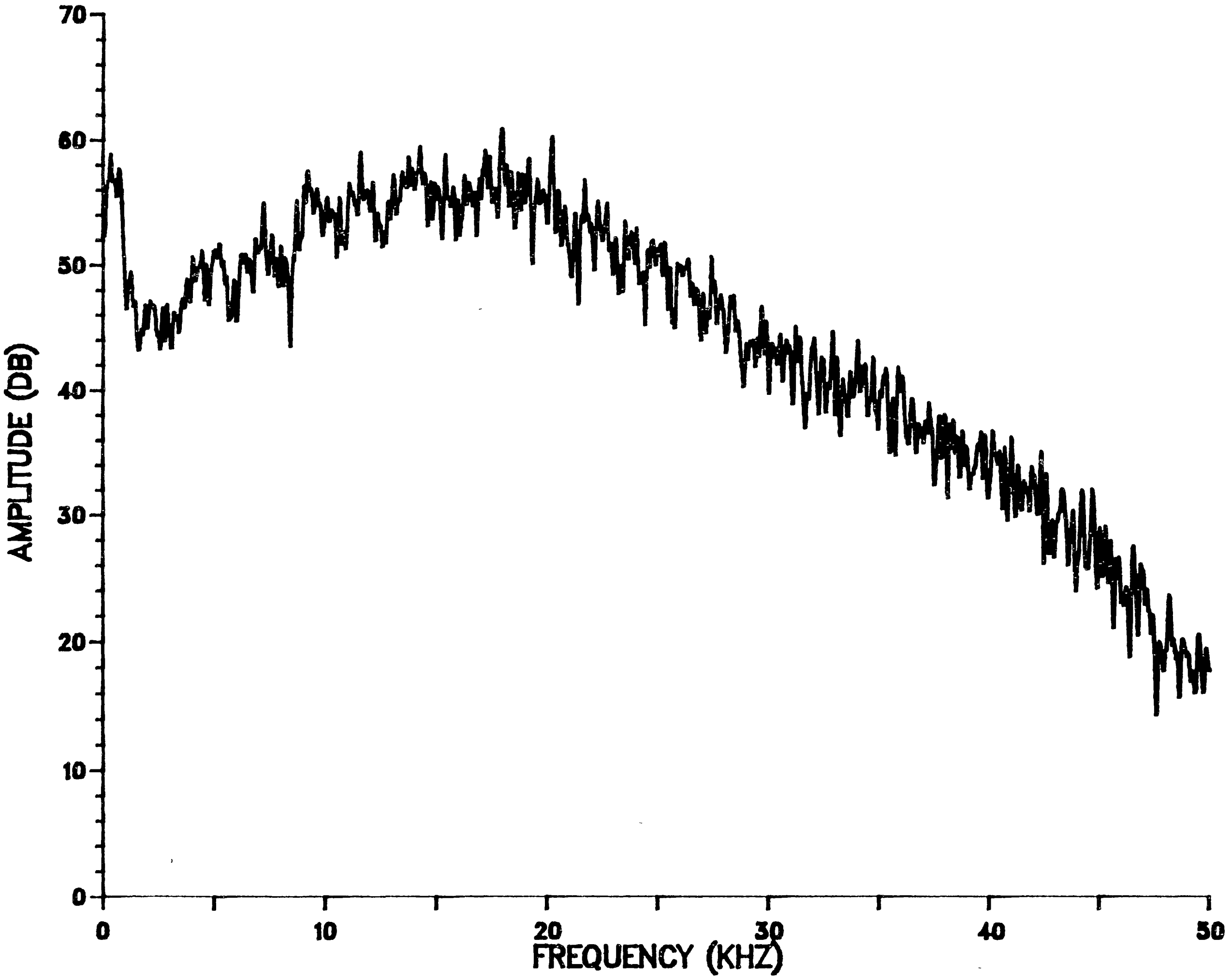


Figure 4. Amplitude versus frequency, moisture content 10%, replication 2

frequencies below 5 kHz were neglected due to sporadic readings and the strong influence of background noise. It was determined that including the readings below 5 kHz would limit the effectiveness of modeling the response curves. In modeling the response curve, the amplitude was chosen as the dependent variable with moisture content and frequency as independent variables.

$$\text{Amplitude} = f\,(\text{Frequency, Moisture content}) \qquad (7)$$

Frequency seemed to have the largest influence on the shape of the curve, and moisture content determined the shift of the curve up and down. The shape of the curve (Figure 4) showed signs of having more than one inflection point, indicating that the amplitude versus frequency relationship might be at least a second-order polynomial equation. The square and cube of the frequency term were used in evaluating the best model.

$$\text{Amplitude} = f\,(F,\ F^2,\ F^3,\ MC,\ F{*}MC,\ F^2{*}MC,\ F^3{*}MC) \qquad (8)$$

SAS Procedure Stepwise was used to determine the best one-to-seven variable models for predicting amplitude as a function of moisture content and frequency. Moisture content, frequency, frequency squared, frequency cubed, and the three interactions between moisture content and the frequency variables were the seven variables evaluated in this model.

All twenty-five of the samples were included in the modeling and the complete results can be found in Appendix B. From the results of the modeling, the five-to-seven variable models showed very little improvement over the four variable model (Table VI). The interaction terms were the ones added to the five-to-seven variable models and showed to be insignificant. The four variable model using moisture content, frequency, frequency squared, and frequency cubed had an R squared of 0.956. Considering the "noise" of the response curves in Figure 4, this correlation proved to be an excellent model of the amplitude as a function of frequency and moisture content.

Figure 5 shows actual versus modeled frequency-amplitude response curves from the four variable model at one of the high moisture contents and at one of the low moisture contents. The figure graphically shows how well the regression equation fits the data.

Figure 6 illustrates the modeled frequency-amplitude regression curves for three different moisture contents. This figure demonstrates that at a particular frequency the drier wheat exhibits a higher amplitude, and this relationship holds across the entire frequency range. These results supported the earlier observation that drier wheat generates more sound than wetter wheat.

TABLE VI

R-SQUARE RESULTS FOR MODELS PREDICTING AMPLITUDE

VARIABLES	R-SQUARE
MC	0.0444
F^2, MC	0.9358
F, F^2, MC	0.9442
F, F^2, F^3, MC	0.9560
F, F^2, F^3, MC, F*MC	0.9591
F, F^2, F^3, MC, F*MC, F^3*MC	0.9596
F, F^2, F^3, MC, F*MC, F^2*MC, F^3*MC	0.9596

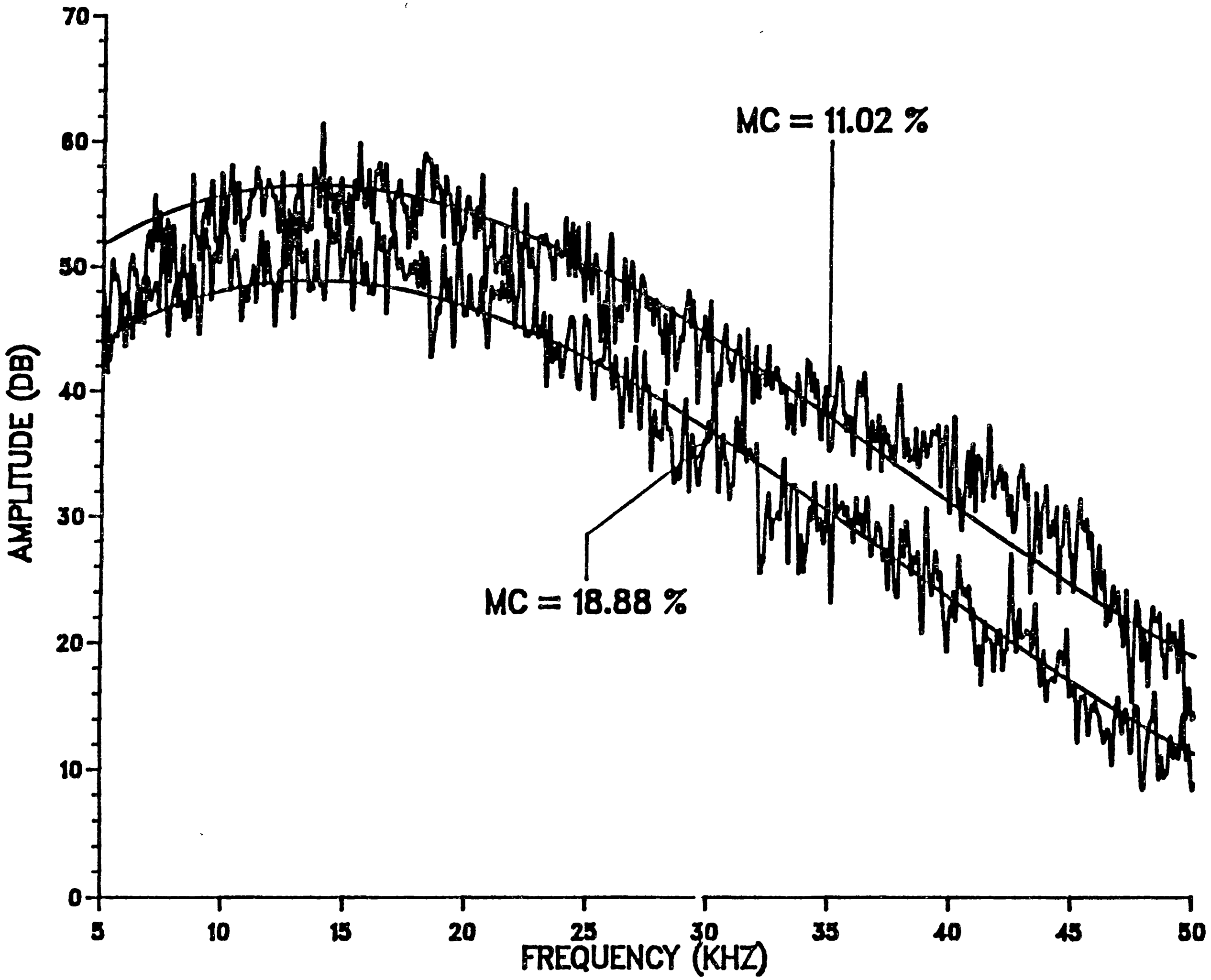


Figure 5. Amplitude-frequency curves for observed data versus modeled data for two moisture contents

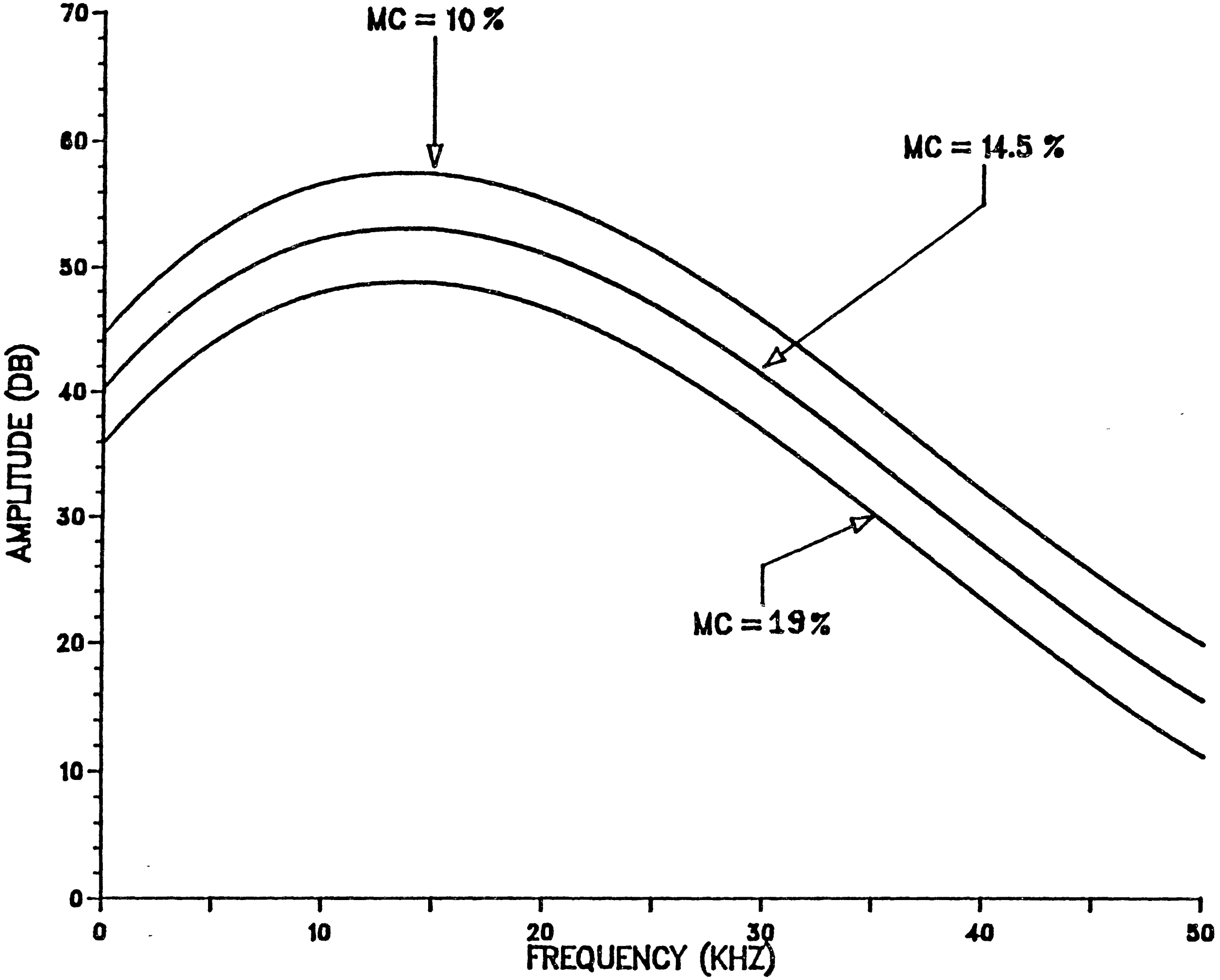


Figure 6. Amplitude versus frequency regression curves for three moisture contents

Area Method

Within certain frequency ranges the difference in amplitudes due to moisture content appears to be greater. Identification of the frequency where the curves were fartherest apart would assist in selecting the frequency at which amplitude is most sensitive to moisture content. A method was developed to select a single frequency where the moisture content could best be predicted with only amplitude data. The method was based on the idea that the area under the amplitude-frequency curve in a particular frequency range might be proportional to moisture content. To approximate the area under the curve, the amplitude readings were summed over a given frequency range. To enable adding amplitude readings, the readings were first converted from the dB scale to sound pressure ratios.

$$\text{Sound pressure ratio} = 10^{(\text{Amp. reading} / 20)} \tag{9}$$

The sound pressure ratios were then added to obtain an approximation of the area (total sound pressure ratio).

$$\text{Area} = F1 + F2 + F3 + \ldots\ldots FN \tag{10}$$

where:

F1 = beginning frequency
FN = ending frequency

The area was then converted back to the dB scale.

$$\text{Area (dB)} = \text{Log}_{10} (20 \text{ X Area}) \qquad (11)$$

The area (total amplitude) was calculated for frequency ranges from 5 kHz to 45 kHz in 5 kHz bands. Because the frequency bands had the same number of amplitude readings, the method of summing the amplitudes was consistent for each frequency band. This method should provide relatively the same results as a sound level meter operating in a specific frequency band.

The results of these calculations are presented in Table VII. A plot of area versus moisture content at 5-10 kHz is shown in Figure 7. (Plots for the other frequency bands evaluated are shown in Appendix C.) A regression analysis was performed on the areas and the moisture contents for each of the frequency bands to determine if specific bands were better than others for linear correlation or for slope. The correlation coefficients and the slopes from the regression analysis are shown in Table VIII. A graphic illustration of the calculated regression lines is shown in Figure 8.

The correlation trend between moisture content and area was fairly consistent throughout the entire frequency range, with some of the frequency bands showing slightly better correlation. The results of the area method were very encouraging, considering the noise in the frequency-

TABLE VII

AREA RESULTS

MC	5-10 KHZ	10-15 KHZ	15-20 KHZ	20-25 KHZ	25-30 KHZ	30-35 KHZ	35-40 KHZ	40-45 KHZ
11.0	96.74	100.04	101.43	97.78	92.63	86.32	81.66	76.15
13.7	94.63	97.72	97.05	94.14	88.15	81.76	77.06	71.33
15.3	94.94	98.49	98.16	95.38	89.94	84.21	78.42	72.40
17.7	92.38	94.87	94.40	89.66	83.73	76.42	70.32	65.23
18.9	92.61	95.82	95.38	91.06	84.02	78.32	72.96	65.23
11.0	96.24	100.01	100.65	97.23	91.71	86.03	81.51	75.89
13.8	94.20	97.21	97.87	94.34	88.03	82.85	77.26	71.33
15.3	95.24	97.60	98.34	94.69	89.17	82.64	78.22	71.80
17.8	92.82	95.78	95.07	90.56	84.56	78.00	72.09	66.46
18.8	92.88	95.25	95.35	91.89	85.18	78.36	73.52	66.21
11.1	97.14	99.74	99.82	95.77	89.19	85.32	81.16	75.00
13.7	94.64	98.06	98.14	94.27	87.87	82.03	77.42	70.44
15.2	95.14	98.84	98.25	94.51	87.54	83.23	77.02	71.79
17.7	92.99	94.76	94.50	90.37	83.16	76.51	71.49	64.90
18.9	93.59	95.20	95.51	91.04	84.84	77.57	71.60	64.90
11.0	96.39	101.25	101.45	98.15	91.70	86.12	81.68	75.97
13.8	94.88	98.58	98.32	94.93	88.49	83.12	77.92	72.77
15.2	95.12	97.28	99.38	95.14	89.67	84.28	78.09	72.37
17.7	92.49	95.22	94.64	91.07	83.75	77.81	72.05	65.25
18.7	93.15	95.44	95.33	91.17	85.07	77.95	72.08	65.73
11.0	96.13	100.00	100.42	96.54	91.41	85.72	81.73	76.47
13.7	94.35	97.78	98.75	95.04	89.05	83.79	77.48	71.12
15.2	95.01	98.11	97.83	94.97	89.27	83.60	77.29	72.75
17.7	92.08	95.70	94.85	91.00	84.81	77.29	71.54	66.27
18.9	92.81	94.96	94.22	90.77	83.95	77.36	72.39	65.44

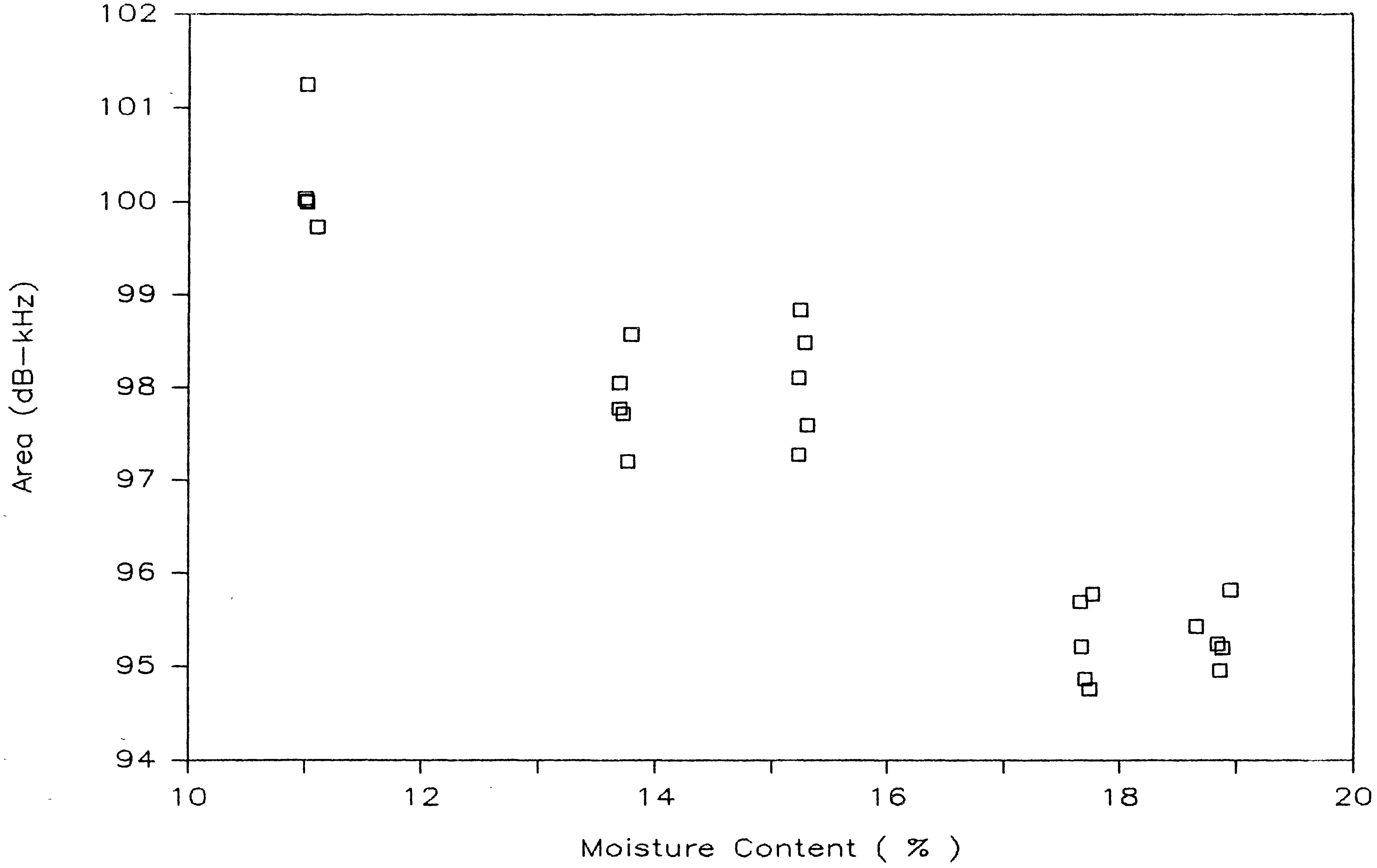


Figure 7. Area versus moisture content at 5-10 kHz

TABLE VIII

AREA VERSUS MOISTURE CONTENT REGRESSION ANALYSIS

FREQUENCY BAND (KHZ)	CORRELATION COEFFICIENT	SLOPE
5-10	- 0.911	-1.733
10-15	- 0.940	-1.367
15-20	- 0.932	-1.135
20-25	- 0.925	-1.029
25-30	- 0.906	-0.880
30-35	- 0.920	-0.753
35-40	- 0.943	-0.706
40-45	- 0.950	-0.653

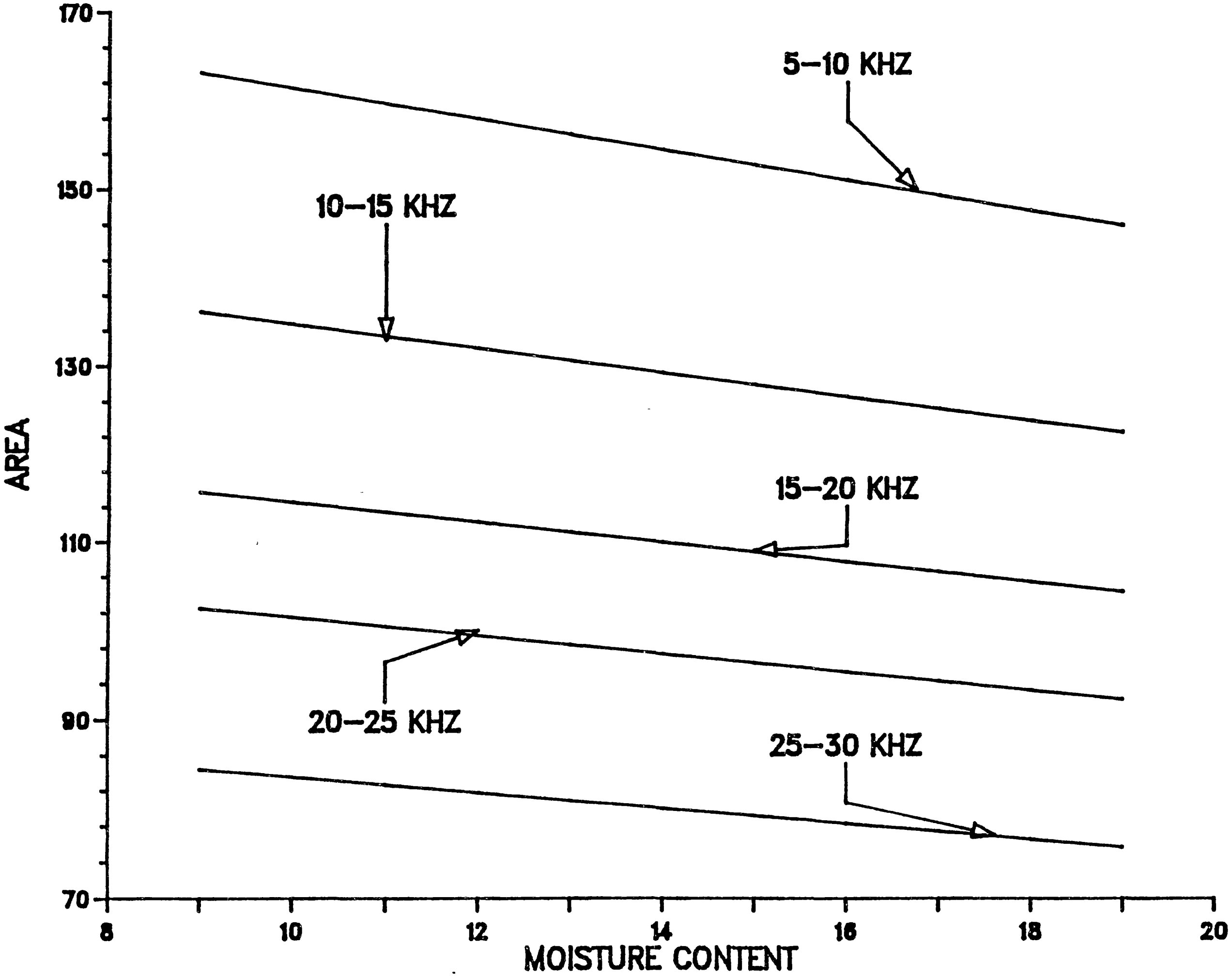


Figure 8. Modeled area versus moisture content at 5 different frequency spaces

amplitude curves and the simple way of calculating the areas.

Repeatability

Using the areas calculated from the amplitude versus frequency curves, the effects of time, sequence, and moisture content were evaluated. The time period needed for five replications was the time effect, and the order in which the moisture levels were tested was the sequence effect. The purpose of the Latin Square experimental design was to block effects due to time and sequence from influencing moisture content. An analysis of variance for each frequency band was performed on the area calculations for the three main effects: time, sequence, and moisture content.

The analysis of variance results (Table IX) show the most prominent effect for each frequency range was moisture content. The time and sequence effects showed signs of being significant in some of the frequency bands, justifying the use of the Latin Square design to insure the blocking of these effects. The effects of time and sequence were overwhelmingly outweighed by the effect of moisture content.

A measure of the repeatability of an area reading and subsequent calculation was deduced from the analysis of variance. The repeatability of the area readings, with a 95 % confidence, was found by taking the square root of the

TABLE IX

AREA ANALYSIS OF VARIANCE FOR MOISTURE CONTENT, SEQUENCE, AND TIME

	AOV SUM OF SQUARES				
FREQUENCY RANGE (KHZ)	MEAN	M.C.	SEQUENCE	TIME	ERROR
5-10	222,523.4	51.8	0.1	1.1	1.0
10-15	236,915.0	86.7	1.6	0.4	3.3
15-20	237,179.5	125.1	1.8	1.3	3.3
20-25	219,302.8	150.6	1.0	2.1	3.7
25-30	191,297.4	192.6	1.7	5.7	6.7
30-35	165,909.3	282.5	2.6	2.3	3.3
35-40	145,018.1	341.4	1.1	1.8	3.5
40-45	122,951.8	405.0	1.5	3.7	2.5

mean square error and multiplying by 1.960. Considering the time and sequence effects as insignificant, the repeatability of a total amplitude reading taken independent of time and sequence was found by adding the degrees of freedom and sum of square errors of the time and sequence effects to the degrees of freedom and sum of square errors of the error term, respectively. The mean square error term was calculated by taking the new sum of squares error term and dividing by the new degrees of freedom error term. The 95 % repeatability was calculated as before by taking the square root of the mean square error and multiplying by 1.960. The calculated repeatability values for a reading at each frequency band for both methods mentioned above are displayed in Table X. One can see from the table that time and sequence had little effect on the repeatability. Repeatablility was adequate, but could definitely be improved.

TABLE X

AREA REPEATABILITY

WITH TIME AND SEQUENCE EFFECTS

FREQ. RANGE (KHZ)	M.S. ERROR	SQUARE ROOT	X 1.96
5-10	0.08117	0.28490	0.55984
10-15	0.27581	0.52518	1.03197
15-20	0.27108	0.52065	1.02308
20-25	0.30871	0.55562	1.09179
25-30	0.55920	0.74780	1.46942
30-35	0.27159	0.52114	1.02405
35-40	0.28751	0.53620	1.05363
40-45	0.20887	0.45702	0.89805

WITH TIME AND SEQUENCE EFFECTS IN THE ERROR TERM

FREQ. RANGE (KHZ)	M.S. ERROR	SQUARE ROOT	X 1.96
5-10	0.10567	0.32507	0.63877
10-15	0.26676	0.51649	1.01491
15-20	0.31536	0.56157	1.10348
20-25	0.34074	0.58373	1.14702
25-30	0.70387	0.83897	1.64858
30-35	0.40617	0.63731	1.25232
35-40	0.31706	0.56308	1.10646
40-45	0.38525	0.62069	1.21965

CHAPTER VI

CONCLUSIONS

The moisture contents of the samples were practically constant during the execution of the experiment. The range of moisture contents was similar to what might be encountered in normal wheat harvest and storage conditions. The frequency spectra was unique for each moisture content, and increasing the moisture content shifted the curve up. Smoothing the amplitude-frequency curves helped to eliminate erratic readings that caused the curves to be difficult to interpret. The modeling of the response curves (Amplitude $= f(F, F^2, F^3, MC, F*MC)$) showed a very good fit for a third degree polynomial equation. Results from the modeling indicate variables such as sequence and time of conducting the experiment were not significant.

The area approximation method used to isolate the optimum frequency range was somewhat successful. The correlation and slope results from the area method indicate that frequencies in the 5-15 kHz range would work adequately for determining moisture content from amplitude readings. It should be noted that equipment and procedures used had an effect on the performance of the frequency bands analyzed. The response curve of the microphone and the C-weighted filter had some effect on the data gathered at the upper frequencies.

The repeatability of the area method displayed a stable method for predicting moisture content. The variability that did exist in the area calculations shows that a method for dampening the "noise" found in the response curves would be necessary.

A procedure was developed to determine the relationship between moisture content and acoustic properties of flowing wheat. The relationship between frequency, moisture content, and amplitude was identified. A method was developed to predict moisture content using amplitude readings within a given frequency range. Particular frequency ranges were found where the moisture content would be easiest to predict. The developed methodology shows that there is potential for building an acoustic based moisture meter for flowing grain.

CHAPTER VII

SUGGESTIONS FOR FURTHER RESEARCH

Many variables in the experimental study were arbitrarily chosen and held constant. Variables such as the type of microphone, microphone distance, drop distance, variety of wheat, etc., need to be varied and monitored to determine which variables are important and to optimize the acoustic method for monitoring moisture content in flowing wheat by using the best values for the important variables.

The results of the area approximation method indicate that a sound analyzing system with band pass filters on each end of the desired frequency band would allow for accurate prediction of moisture level in flowing wheat. The frequency range from 5-15 kHz would be an ideal range to monitor, since the correlation and slope results of the area method were good in this range, and because lower frequency equipment is relatively inexpensive and readily available.

The time required to capture an acoustic sample should be sufficiently long to allow for an averaging of the amplitude response. "Smoothing" the data this way would be much easier and direct than sampling rapidly and smoothing the data later. Results from additional work should help determine the accuracy and feasability of measuring moisture content in wheat using acoustic properties.

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APPENDIX A

LISTING OF BASIC DATA STORAGE PROGRAM

```
  5  HOME
  6  GOSUB 1000: REM DISK DEFAULTS
 10  REM  PROGRAM FOR A/D
 15  DIM C0%(2500),C1%(2500)
 20  HTAB 10
 21  PRINT "HIT ANY KEY WHEN READY"
 22  HTAB 10
 23  PRINT "TO BEGIN SAMPLING"
 24  HTAB 18
 25  GET Z$
 30  K1=279/4095
 40  K2=191/4095
 50  K3=191
 60  SL=3
 70  HGR2
 80  HPLOT 0,0 TO 279,0 TO 279,191 TO 0,191 TO 0,0
 90  AD= -16256 + (SL * 16)
 95  POKE (AD),0
100  GO TO 95
105  I=1
110  POKE (AD),0
120  C0%(I) = PEEK (AD+1) * 256 + PEEK (AD)
130  POKE (AD),1
140  C1%(I) = PEEK (AD + 1) * 256 + PEEK(AD)
142  IF C0%(I) > 4094 THEN GO TO 145
143  I =I + 1
144  GO TO 110
145  N = 1
146  PRINT CHR$ (7)
147  FOR I = 1 TO N
150  X=C0%(I) * K1
160  Y=K3 - C1%(I) * K2
163  X= INT (X+ 0.5)
165  Y= INT (Y+ 0.5)
170  HPLOT X,Y
180  NEXT I
190  PRINT CHR$ (7)
200  GET Z$: HOME
305  TEXT
306  HOME : PRINT
308  HTAB 5
310  INPUT " SAVE DATA TO DISK ? (Y/N)  ";ANS$
320  IF ANS$ = "N" THEN GO TO 340
330  IF ANS$ = "Y" THEN GO TO 370
331  DQ = PEEK (37)
332  DQ = DQ - 1
333  VTAB (DQ)
335  PRINT CHR$ (7) : GO TO 308
340  POKE 49232,0: POKE 49237,0
350  GET Z$
360  TEXT: HOME : GO TO 20
370  REM  STORE DATA IN FILE ON DISK
380  REM  INPUT FILE HEADER
385  HOME : VTAB 5
```

```
 386   PRINT "NUMBER OF POINTS IS  ";N
 387   PRINT
 390   INPUT "SAMPLE NUMBER ?                 ";SN$
 395   PRINT
 400   INPUT "LOWER FREQUENCY ? ( IN KHZ )    ";LF$
 405   PRINT
 410   INPUT "HIGHER FREQUENCY ? ( IN KHZ )     ";HF$
 420   HOME
 430   REM  DISPLAY HEADER INFO.
 440   GOSUB 2000
 500   VTAB 20
 510   INPUT "CHANGE ANY VALUES ?    (Y/N)   ";ANS$
 520   IF ANS$ = "N" THEN GO TO 550
 530   IF ANS$ = "Y" THEN GO TO 580
 535   RQ = PEEK (37)
 536   RQ = RQ-1
 537   VTAB (RQ)
 540   PRINT CHR$ (7): GO TO 550
 550   TEXT : HOME : VTAB 20 : HTAB
 551   INPUT "SMOOTH DATA    ?  (Y/N)   ";ANS$
 552   IF ANS$ = "N" THEN GO TO 568
 553   IF ANS$ = "Y" THEN GO TO 565
 554   RQ = PEEK (37)
 555   RQ = RQ-1
 556   VTAB (RQ)
 557   PRINT CHR$ (7) : GO TO 550
 565   GO TO 6000
 568   GO SUB 5000
 570   STOP
 580   REM    GET CHANGES
 590   GO SUB 4000
 600   REM   RESET CURSOR WINDOW
 610   GO SUB 4500
 620   REM  GO BACK TO TABLE AND INSURE NO CHANGES NEEDED
 630   GO TO 420
1000   REM  INITIALIZE DISK HEADER DEFAULTS
1010   PRINT
1080   REM  RB=RESOLUTION BANDWIDTH
1090   RB$ = "300"
1100   REM  SM=SMOOTHING
1110   SM$ = "MAX"
1120   REM  SW=SWEEP TIME / DIV.
1130   SW$ = "2"
1140   REM  SE=SOUND METER SENSITIVITY
1150   SE$ = "70 DB"
1160   REM  FL=FILTER
1170   FL$ = "NONE"
1180   REM  SC=SCALE USED
1190   SC$ = "10.0 LOG"
1200   REM  MC=MOISTURE CONTENT
1210   MC$ = "0.0"
1220   REM  IS=INPUT SENSITIVITY
1230   IS$ = "+ 10 DB"
1240   RETURN
```

```
2000   REM  DISPLAY HEADER INFO.
2010   HOME
2020   PRINT : PRINT : PRINT
2030   REM  SET TAB FOR DATA COLUMN
2040   TB = 30
2050   PRINT "  SAMPLE #"; TAB (TB) SN$
2060   PRINT "  LOWERE FREQ."; TAB (TB)LF$ TAB(35);"KHZ"
2070   PRINT "  HIGHER FREQ."; TAB (TB)HF$ TAB(35);"KHZ"
2080   PRINT "  RES. B.W. "; TAB (TB)RB$
2090   PRINT "  SMOOTHING"; TAB (TB)SM$
2100   PRINT "  SWEEP TIME/DIV."; TAB (TB)SW$
2110   PRINT "  SOUND METER SENS."; TAB (TB)SE$
2120   PRINT "  FILTER"; TAB (TB)FL$
2130   PRINT "  SCALE";  TAB (TB)SC$
2140   PRINT "  MOISTURE CONTENT"; TAB (TB)MC$
2150   PRINT "  INPUT SENS."; TAB (TB)IS$
2160   RETURN
2900   REM  SUBROUTINE FOR INPUTING NEW VARIABLE VALUES
2905   ON P GO TO 3000,3020,3040,3060,3080,3100,3120,3140,
2906   3160,3180,3200
2907   REM
3000   INPUT SN$
3010   RETURN
3020   INPUT LF$
3030   RETURN
3040   INPUT HF$
3050   RETURN
3060   INPUT RB$
3070   RETURN
3080   INPUT SM$
3090   RETURN
3100   INPUT SW$
3110   RETURN
3120   INPUT SE$
3130   RETURN
3140   INPUT FL$
3150   RETURN
3160   INPUT SC$
3170   RETURN
3180   INPUT MC$
3190   RETURN
3200   POKE 35,15
3202   INPUT IS$
3206   POKE 35,14
3210   RETURN
4000   VTAB 20
4010   PRINT "  MOVE UP & DOWN WITH ARROW KEYS   "
4020   PRINT "  HIT SPACE BAR TO CHANGE A VALUE  "
4030   PRINT "  HIT ESC KEY WHEN VALUES ARE CORRECT"
4040   REM  SET CURSOR WINDOW
4050   POKE 32,28:  REM LEFT
4060   POKE 33,1:  REM WIDTH
4070   POKE 34,3:  REM TOP
4080   POKE 35,14:  REM BOTTOM
```

```
4085  HOME
4090  VX=49152:  REM GET KEYBOARD ADDRESS
4100  VX=49168:  REM PAUSE FOR NEXT KEY ADDRESS
4105  GET XX$
4110  WW = PEEK (VX)
4112  WW = WW + 128
4120  IF WW = 155 THEN RETURN
4130  IF WW = 149 THEN GO TO 4210
4140  IF WW = 136 THEN GO TO 4250
4150  IF WW < > 160 THEN GO TO 4290
4160  XX = PEEK (37)
4170  P = XX-2
4183  POKE 32,29: POKE 33,9
4184  GOSUB 2900
4185  POKE 32,28: POKE 33,1
4186  DD = PEEK (37)
4187  HOME : VTAB (DD)
4188  REM
4195  WW = PEEK (VW)
4200  GO TO 4105
4210  REM LEFT ARROW
4220  DD = PEEK (37)
4225  DD = DD + 2
4227  IF DD = 15 GO TO 4235
4230  VTAB (DD)
4235  REM
4240  GO TO 4195
4250  REM RIGHT ARROW
4260  DD = PEEK (37)
4265  IF DD = 3 GO TO 4275
4270  VTAB (DD)
4275  REM
4280  GO TO 4195
4290  REM  NOT SPACE BAR
4300  PRINT CHR$ (7)
4310  GO TO 4195
4500  POKE 32,0
4510  POKE 33,40
4520  POKE 34,0
4530  POKE 35,24
4540  RETURN
5000  REM  SUBROUTINE FOR WRITING DATA TO DISK
5020  FILE$ = "W" + SN$ + "-" + MC$
5030  D$ = CHR$ (4)
5040  PRINT D$;"OPEN ";FILE$
5050  PRINT D$;"WRITE ";FILE$
5055  PRINT N
5060  PRINT SN$
5070  PRINT LF$
5080  PRINT HF$
5090  PRINT RB$
5100  PRINT SM$
5110  PRINT SW$
5120  PRINT SE$
```

```
5130  PRINT FL$
5140  PRINT SC$
5150  PRINT MC$
5160  PRINT IS$
5170  FOR I = 1 TO N
5180  PRINT C0%(I)
5190  PRINT C1%(I)
5200  NEXT I
5205  PRINT D$;"CLOSE ";FILE$
5210  RETURN
6000  REM  PART OF PROGRAM FOR SMOOTHING
6002  HGR2
6004  HPLOT 0,0 TO 279,0 TO 279,191 TO 0,191 TO 0,0
6010  Z1 = C1%(1)
6020  C1%(1) = (C1%(1) + C1%(2) ) / 2
6030  FOR I = 2 TO (N-1)
6040  Z2 = C1%(I)
6050  C1%(I) = (Z1 + Z2 + C1%(I + 1) ) / 3
6060  Z1 = Z2
6070  NEXT I
6080  C1%(N) = (Z2 C1%(N) ) / 2
6090  FOR I = 1 TO N
6100  X = C0%(I) * K1
6110  Y = K3 - C1%(I) * K2
6120  HPLOT X,Y
6123  NEXT I
6125  PRINT CHR$ (7)
6130  GET Z$
6140  HOME : TEXT
6150  GO TO 550
```

APPENDIX B

MODELING RESULTS

```
MAXIMUM R-SQUARE IMPROVEMENT FOR DEPENDENT VARIABLE AMPL


STEP 0 INCLUDED VARIABLE ENTERED


R SQUARE=0.04443095


C(P)=859888.478127


           DF   SUM OF SQUARES  MEAN SQUARE      F    PROB>F

REGRESSION  1      278122.2387  278122.2387  1764.14  0.001

ERROR   37941     5981528.3576     157.6534

TOTAL   37942     6259650.5963


           B VALUE   STD ERROR   TYPE II SS    F     PROB>F

INTERCEPT   46.1954

MC          -0.9673   0.02303   278122.2387  1764.14  0.0001
```

```
MAXIMUM R-SQUARE IMPROVEMENT FOR DEPENDENT VARIABLE AMPL


STEP 2 VARIABLE FREQ2 ENTERED


R SQUARE=0.935785

    C(P)=22397.5837

             DF   SUM OF SQUARES  MEAN SQUARE      F        PROB>F

REGRESSION  2   5857688.0454  2928844.0227  276444.51  0.0001

ERROR    37940    401962.5509        10.5947

TOTAL    37942  6259650.5963


              B VALUE   STD ERROR  TYPE II SS       F        PROB>F

INTERCEPT  61.5156

MC           -0.9712  0.00597   280385.5599   26464.72  0.0001

FREQ2        -0.0166  0.00002  5579565.8067  526637.93  0.0001
```

```
MAXIMUM R-SQUARE IMPROVEMENT FOR DEPENDENT VARIABLE AMPL


STEP 3 VARIABLE FREQ ENTERED


R SQUARE=0.944186

    C(P)=859888.478127


            DF   SUM OF SQUARES   MEAN SQUARE     F      PROB>F

REGRESSION   3    5910278.8866   1970092.9622  213936   0.0001

ERROR      37939   349371.7097         9.2088

TOTAL      37942  6259650.5963


           B VALUE   STD ERROR  TYPE II SS      F       PROB>F

INTERCEPT  56.5659

MC         -0.9716   0.00557  280566.9171   30467.34  0.0001

FREQ2      -0.0242   0.00010  509650.8142   55344.04  0.0001

FREQ        0.4364   0.00578   52590.8412    5710.95  0.0001
```

```
MAXIMUM R-SQUARE IMPROVEMENT FOR DEPENDENT VARIABLE AMPL


STEP 4 VARIABLE FREQ3 ENTERED


R SQUARE=0.955991

    C(P)=3416.8689


                DF   SUM OF SQUARES   MEAN SQUARE      F         PROB>F

REGRESSION   4   5984168.4798   1496042.1200   206027.33   0.0001

ERROR    37938    275482.1163          7.2614

TOTAL    37942   6259650.5963


               B VALUE    STD ERROR   TYPE II SS        F       PROB>F

INTERCEPT 46.5771

MC          -0.9708    0.00494    280170.4725    38583.66   0.0001

FREQ3        0.0008    0.00001     73889.5934    10175.70   0.0001

FREQ2       -0.0908    0.00066    134820.8154    18566.84   0.0001

FREQ         2.0187    0.01650    108658.2890    14963.87   0.0001
```

```
MAXIMUM R-SQUARE IMPROVEMENT FOR DEPENDENT VARIABLE AMPL


STEP 5 VARIABLE INT1 ENTERED


R SQUARE=0.959067


    C(P)=528.8036


           DF   SUM OF SQUARES  MEAN SQUARE      F       PROB>F

REGRESSION  5   6003422.7448  1200684.5490  177772.91  0.0001

ERROR    37937   256227.8515        6.7540

TOTAL    37942  6259650.5963


           B VALUE   STD ERROR  TYPE II SS      F        PROB>F

INTERCEPT  38.3860

MC         -0.4355   0.01111    10395.1456   1539.10   0.0001

FREQ3       0.0008   0.00001    73735.8363  10917.30   0.0001

FREQ2      -0.0908   0.00064   134641.1323  19934.92   0.0001

FREQ        2.3169   0.01686   127438.3421  18868.47   0.0001

INT1       -0.0196   0.00037    19254.2648   2850.78   0.0001
```

```
MAXIMUM R-SQUARE IMPROVEMENT FOR DEPENDENT VARIABLE AMPL

STEP 6 VARIABLE INT3 ENTERED

R SQUARE=0.959449

    C(P)=170.75310

              DF   SUM OF SQUARES MEAN SQUARE      F       PROB>F

REGRESSION   6   6005821.4820  1000970.2470  149599.89  0.0001

ERROR    37936    253829.1143         6.6910

TOTAL    37942   6259650.5963

              B VALUE   STD ERROR    TYPE II SS    F       PROB>F

INTERCEPT  34.4758

MC          -0.1805   0.01742     717.92223   107.30   0.0001

FREQ3        0.0007   0.00001    35426.4267  5294.65   0.0001

FREQ2       -0.0908   0.00064   134745.3861 20138.36   0.0001

FREQ         2.5979   0.02241    89940.8195 13442.09   0.0001

INT1        -0.0379   0.00103     8985.5794  1342.94   0.0001

INT3         0.0001   0.00001     2398.7372   358.50   0.0001
```

```
MAXIMUM R-SQUARE IMPROVEMENT FOR DEPENDENT VARIABLE AMPL


STEP 6 FREQ3 REPLACED BY INT2

R SQUARE=0.959609

    C(P)=20.953115


          DF   SUM OF SQUARES MEAN SQUARE      F        PROB>F

REGRESSION  6   6006819.4831   1001136.5805  150215.36  0.0001

ERROR    37936   252831.1132         6.6647

TOTAL    37942  6259650.5963


           B VALUE   STD ERROR   TYPE II SS      F       PROB>F

INTERCEPT  43.5967

MC         -0.7719    0.02218    8075.9698    1211.76    0.0001

FREQ2      -0.0324    0.00049   29465.0778    4421.08    0.0001

FREQ        1.1836    0.02732   12508.7471    1876.87    0.0001

INT1        0.0538    0.00200    4823.4713     723.74    0.0001

INT2       -0.0038    0.00005   36424.4280    5465.30    0.0001

INT3        0.0005    0.00001   75268.9712   11293.72    0.0001
```

```
MAXIMUM R-SQUARE IMPROVEMENT FOR DEPENDENT VARIABLE AMPL


STEP 7 VARIABLE FREQ3 ENTERED


R SQUARE=0.959625

    C(P)=8.000000


            DF  SUM OF SQUARES MEAN SQUARE      F    PROB>F

REGRESSION   7  6006919.1041  858131.3006  128805.52  0.0001

ERROR    37935   252731.4921       6.6622

TOTAL    37942  6259650.5963


            B VALUE   STD ERROR   TYPE II SS    F       PROB>F

INTERCEPT  41.5587

MC         -0.6431    0.04002    1720.6804   258.27    0.0001

FREQ3       0.0002    0.00004      99.6210    14.95    0.0001

FREQ2      -0.0460    0.003549   1117.6448   167.76    0.0001

FREQ        1.5067    0.08790    1957.3139   293.79    0.0001

INT1        0.0334    0.00565     233.3150    35.02    0.0001

INT2       -0.0029    0.00023    1097.6222   164.75    0.0001

INT3        0.0001    0.00001    1563.0289   234.61    0.0001
```

APPENDIX C

GRAPHS OF AREA VERSUS MOISTURE CONTENT

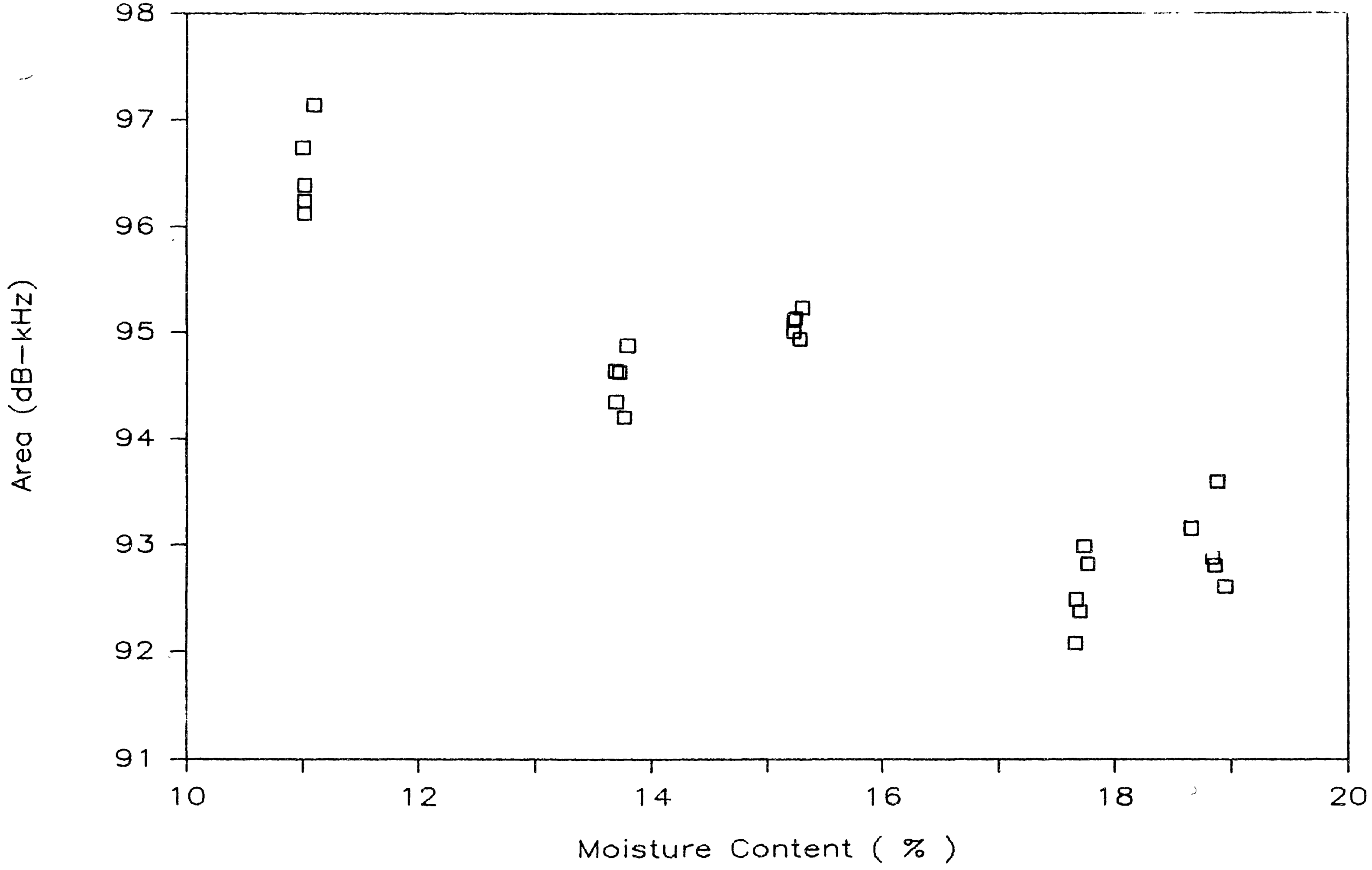

Figure 9. Area versus moisture content at 10-15 kHz

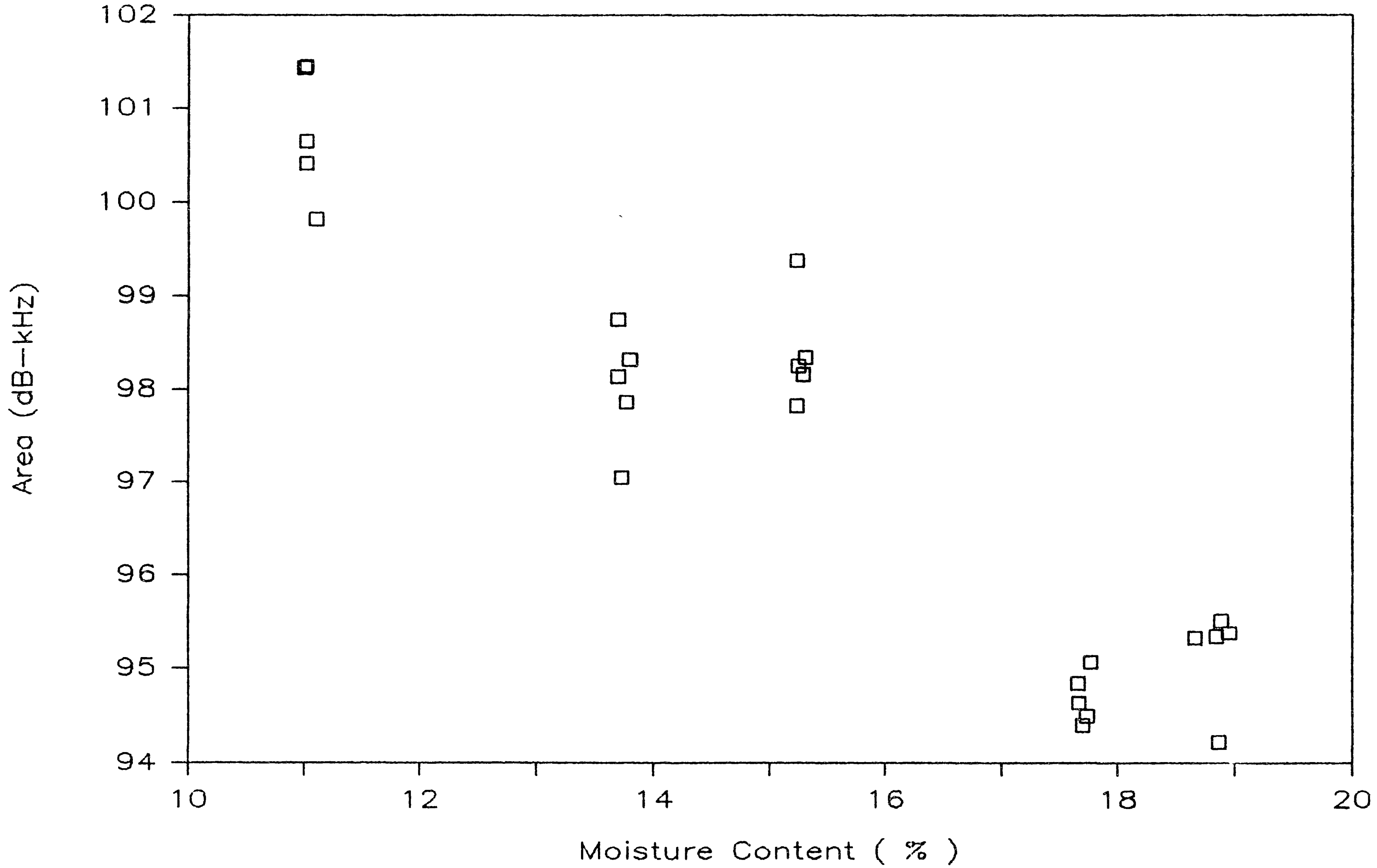

Figure 10. Area versus moisture content at 15-20 kHz

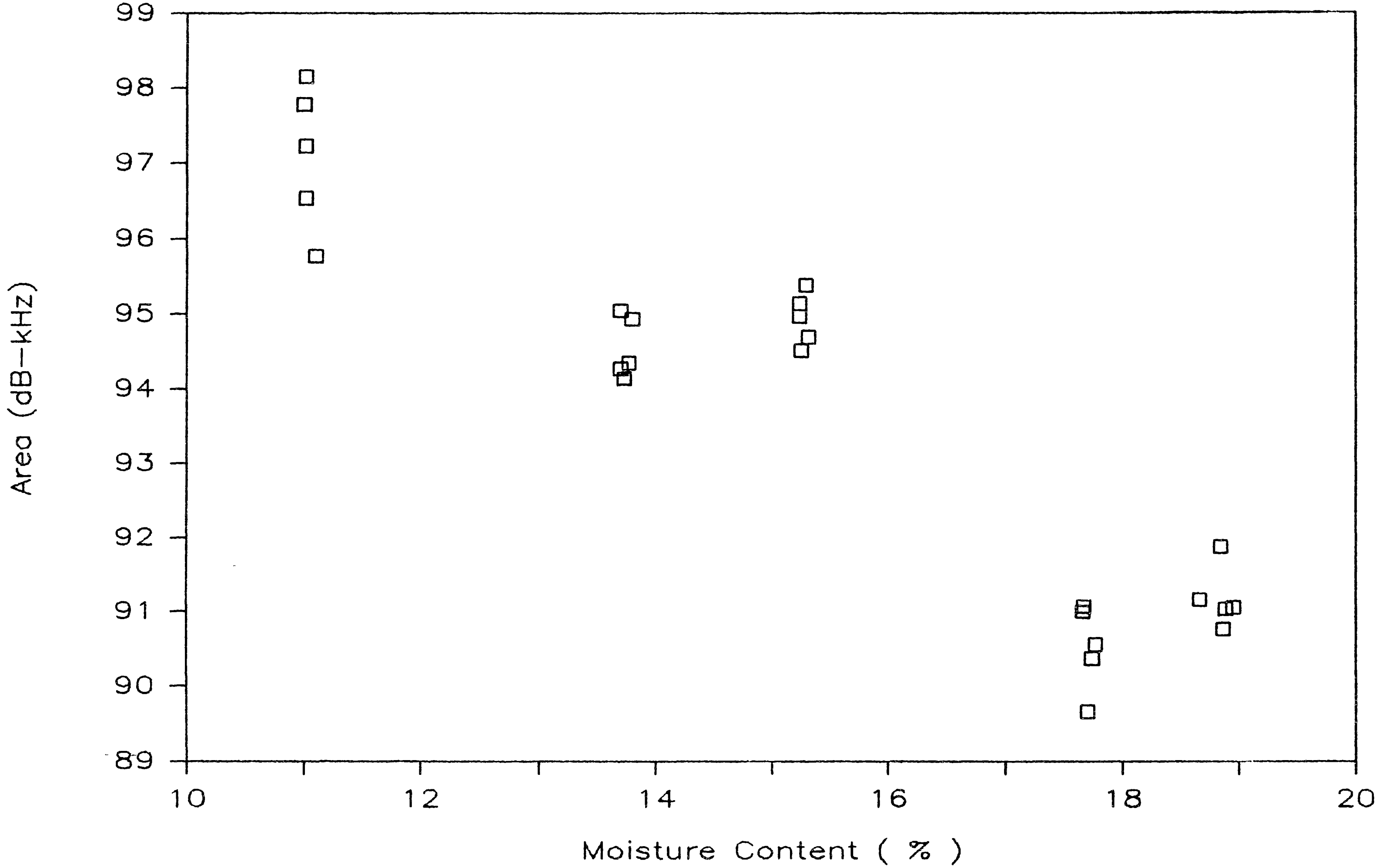

Figure 11. Area versus moisture content at 20-25 kHz

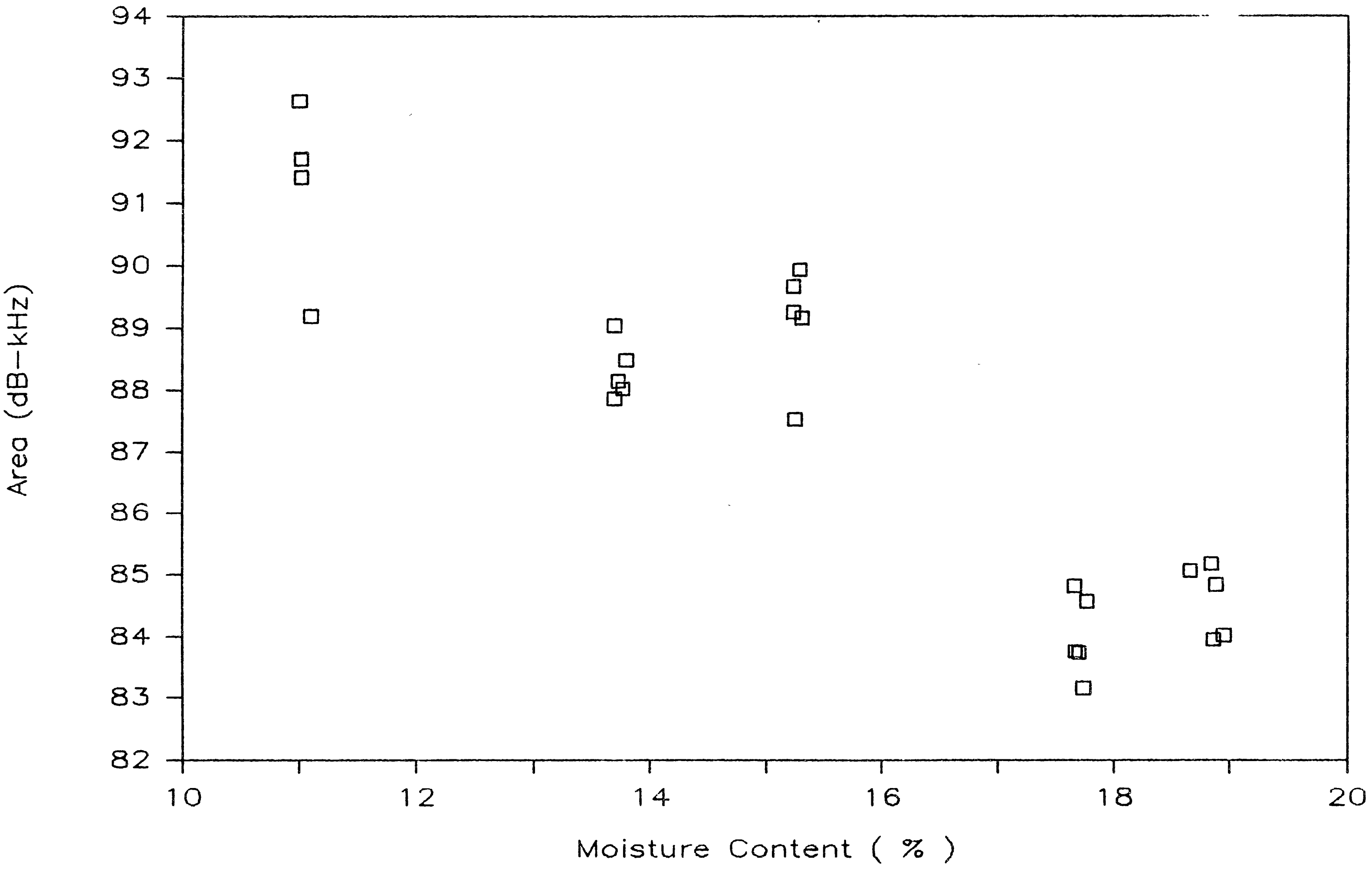

Figure 12. Area versus moisture content at 25-30 kHz

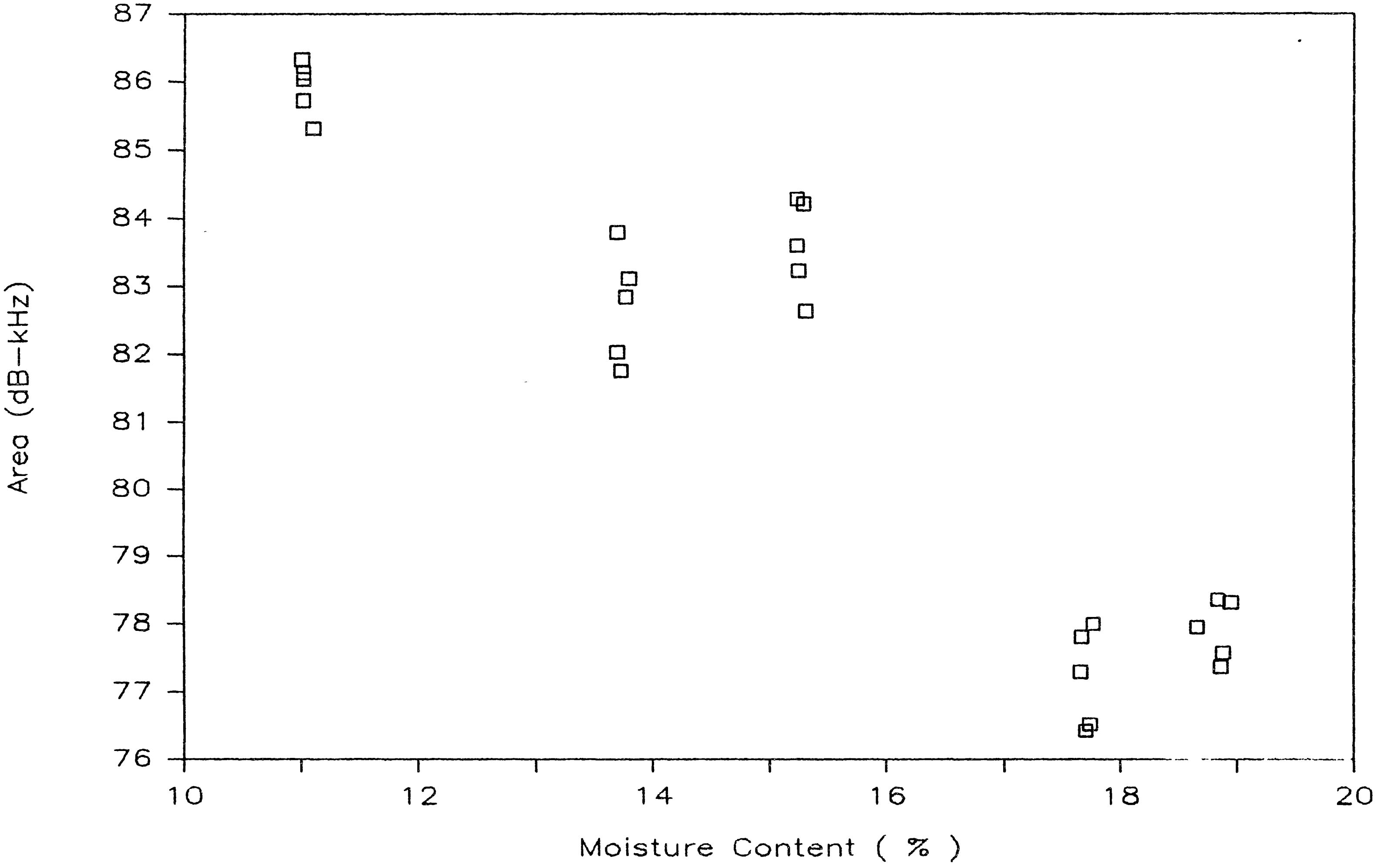

Figure 13. Area versus moisture content at 30-35 kHz

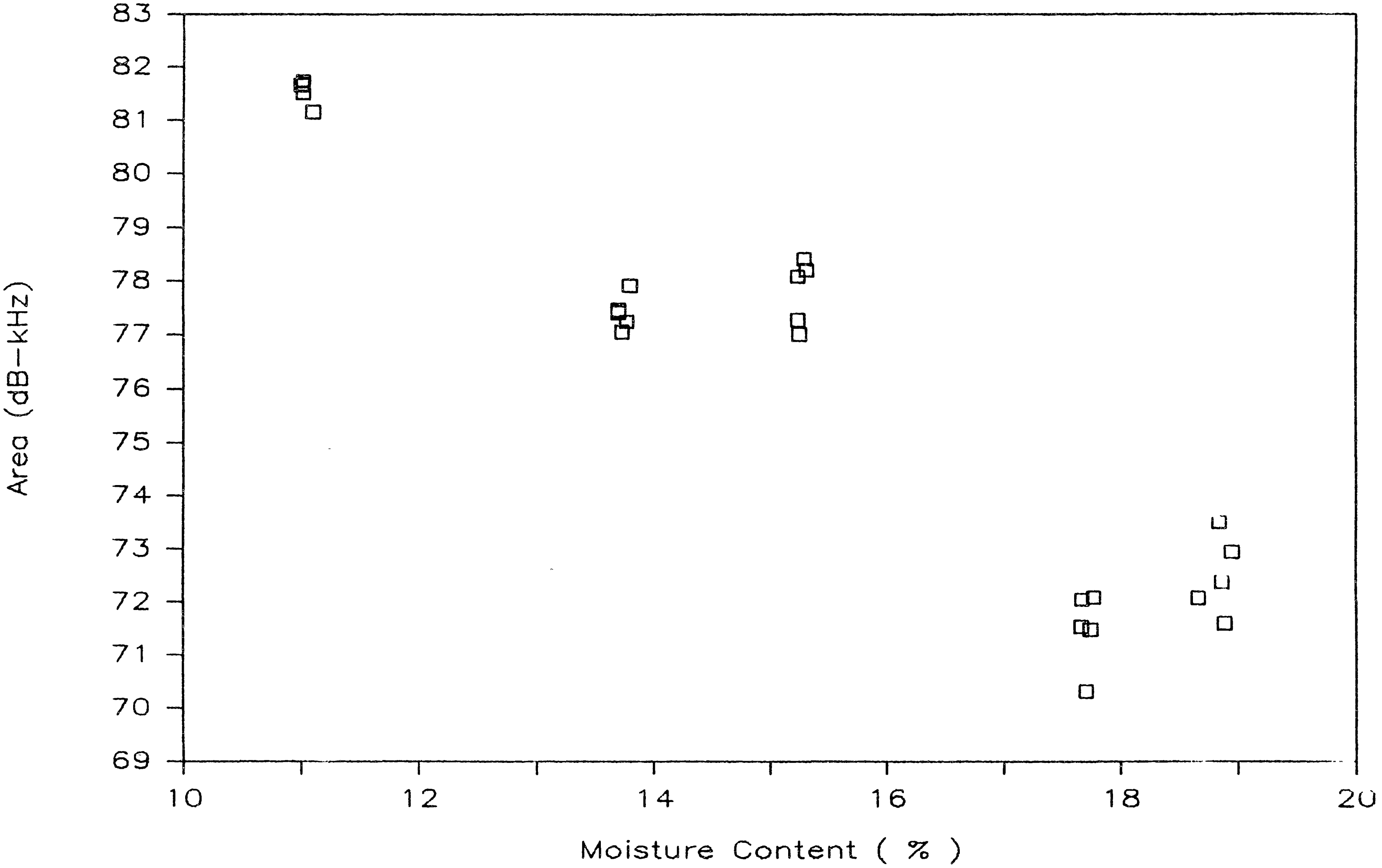

Figure 14. Area versus moisture content at 35-40 kHz

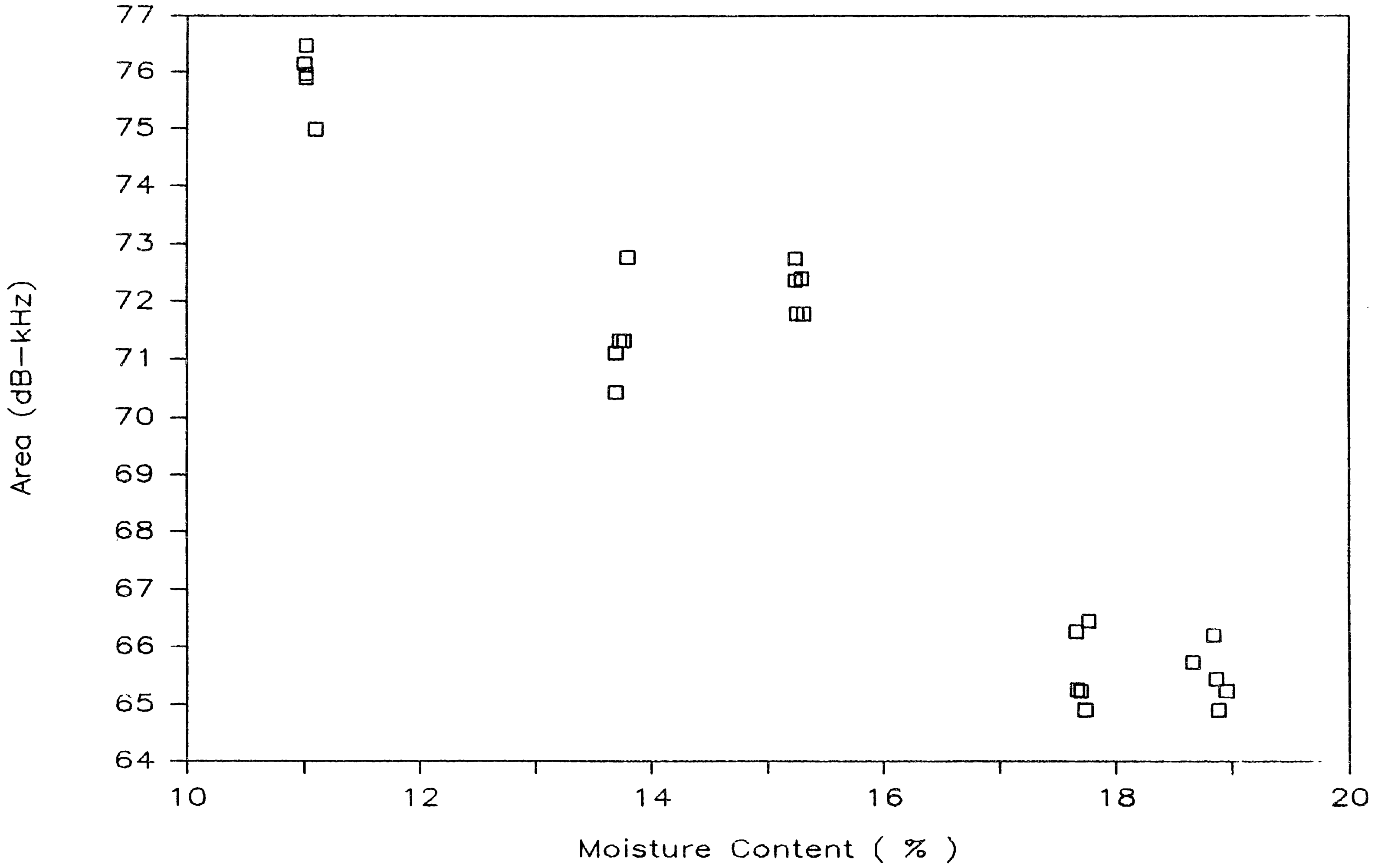

Figure 15. Area versus moisture content at 40-45 kHz

VITA

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