CONCEPT EVALUATION OF AN ULTRASONIC MASS FLOW SENSOR

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Abstract

Two experiments were conducted in an effort to determine the relationship between ultrasound attenuation and lint cleaner waste density. The first experiment indicated that there was a strong correlation between ultrasound attenuation and cotton fiber density. The experiment also demonstrated a temperature dependence of ultrasound attenuation and no significant humidity influence. The second experiment developed the relationship between lint cleaner waste components and ultrasound attenuation. This investigation revealed that waste composed of mote trash attenuated ultrasound approximately two times greater than waste consisting of stick or leaf trash.

Introduction

As the U.S. cotton industry enters the twenty-first century, it is faced with increasing production costs, a highly volatile market and increasing global competition. As a result, cotton producers (farmers) and processors (ginners) must annually reevaluate new technology and techniques to increase productivity and price without lowering fiber quality.

This movement toward higher productivity, coupled with the computer revolution, has driven many producers into the precision agriculture arena. Precision agriculture (a.k.a. site-specific agriculture) simply refers to a production technique that often uses sensors and computers to monitor specific field areas and prescribe treatments to improve production efficiency of those areas.

The same trend can be observed in the cotton processing plant (gin); computers are beginning to be used to monitor and control processing equipment. This technique is referred to as process control and has been used in other industries for years. Process control algorithms are used to make real-time decisions about machine treatments, using on-line measurements of input and output material parameters. USDA-ARS researchers have already laid the foundation for gin process control. However, there are many important areas that are yet to be explored. For example, several researchers have demonstrated that lint cleaner parameters (e.g. combing ratio, saw speed, number of grid bars) can be modified to optimize cleaning efficiency as well as minimize lint wastage (Mangialardi, 1970; Baker, 1977; Anthony, 1999). In fact, Baker (1977) developed equations that describe the performance of lint cleaners. However, he also hypothesized that the accuracy of these equations is greatly influenced by the immeasurable parameters (e.g. variety, location, weather, etc.) associated with production. As a result, the use of these equations for real-time process control does not seem to be feasible (Cook and Anthony, 2001).

To truly optimize cleaning efficiency and minimize lint wastage, a lint cleaner waste mass flow sensor must be developed. Only a few researchers have attempted to develop such a device (Thomasson et al., 1999), and their success is questionable (Whitelock, 1998; Whitelock and Thomson, 1998). Most of the research in this area has focused on the development of seed cotton flow sensors (Taylor, 1962; Wilkerson, 1994; Gvili, 1998; Barker et al., 1999; Funk et al., 2000; Moody et al., 2000). Other research has focused on the evaluation of commercially available yield monitors (Wallace et al., 1998; Durrence et al., 1999; Sassenrath-Cole et al., 1999; Wolack et al., 1999). While some researchers have been more successful than others, almost all have attempted to correlate the interruption of light with the volumetric flow rate of material. This technique seems to work reasonably well, if the light emitters/detectors remain clean and the flow pattern is clearly understood.

An alternative to optical or light-based measurement is acoustical measurement. Acoustical measurement devices usually operate at frequencies above the audible range of the human ear (20 kHz) and below 500 kHz (Lynnworth, 1995; Manthey et al., 1992). These high frequency acoustic waves are called ultrasonic waves or ultrasound. There are several advantages and disadvantages associated with each method. One advantage associated with ultrasound is that ultrasonic pressure waves pass (more or less) through all materials, while light is generally limited to gases, liquids and transparent or translucent solids. As a result, ultrasonic transducers are much less susceptible to attenuation changes caused by dust buildup. This could prove beneficial for the measurement of pneumatically conveyed lint cleaner waste, which can be characterized as a type of gas-solid flow that often contains a significant amount of dust.

Only a few researchers have discussed the use of ultrasonic techniques in gas-solid flow (Brown et al., 1996; Sowerby et al., 1991). Brown explained that there are several key issues that must be clearly understood in order to successfully apply ultrasound to gas-solid flow. These issues are outlined below.

i) Due to the high impedance of most pipe wall material, noninvasive use of ultrasonic transducers is currently considered impractical.
ii) The dynamic nature and high velocity of the carrier gas combined with the relatively low propagation velocity of sound forces the ultrasonic signals to be monitored frequently. As a result, high-speed data acquisition systems are often needed.
iii) Conveyed objects with dimensions much smaller than the ultrasonic wavelength produce Rayleigh scattering, diffraction and absorption. Otherwise, reflection predominates and diffraction effects can be considered negligible.

According to these guidelines, noninvasive or clamp on transducers are not feasible, and all preliminary data processing should be performed in the analog domain to reduce the costs associated with high-speed data acquisition systems. Because cotton fibers have cross sectional dimensions that range from 0.0001 to 0.002 inches (Merrill and Macomac, 1949), it is also reasonable to conclude that lint cleaner waste, which contains a large amount of lint cotton (Mangialardi, 1972), will scatter, diffract or absorb ultrasound at frequencies approaching 500 kHz. This conclusion suggests that as lint cleaner waste density increases ultrasound attenuation will also increase and consequently may be used to measure density. However, lint cleaner waste also contains other constituents such as mote trash and stick or leaf particle trash (see Figure 1). Therefore, the ultrasound attenuation may also be influenced by these components.

Ultrasound attenuation is also affected by properties of the propagation medium. Kocis and Figura (1996) discussed these medium effects. They explained that the theoretical attenuation (α) of ultrasound also depends on losses caused by propagation medium viscosity (α_V), thermal conductivity (α_T) and suggested that the relationships may be expressed as follows.

$$\alpha = \alpha_V + \alpha_T = \frac{2\pi^2}{\rho\left(c^3\right)}\left[\frac{4}{3}\eta + \lambda_T\left(\frac{1}{c_v} - \frac{1}{c_p}\right)\right]f^2 \qquad (1)$$

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where	ρ	=	density[kg/m^3]
	c	=	ultrasound velocity[m/s]
	η	=	dynamic viscosity[Pa*s]
	λ_T	=	thermal conductivity[W/(m*K)]
	c_v , c_p	=	specific heats at constant volume and constant pressure respectively[J/(kg*K)]
	f	=	frequency[Hz]

It is immediately apparent from this equation that aside from frequency, temperature and humidity affect ultrasound attenuation. Therefore, a temperature and/or humidity compensation scheme may be needed to correct for attenuation changes caused by fluctuation of air temperature or relative humidity.

Objectives

The overall goal of this study was to evaluate an ultrasonic mass flow sensor concept. Toward this end, two objectives were defined. The primary objective was to determine the relationship between ultrasound attenuation and lint cleaner waste density. The secondary objective was to understand the temperature and relative humidity affects on ultrasonic pressure wave attenuation.

Methodology

The first step in the experimental phase of research was to create an ultrasonic transmission measurement apparatus. Because the objectives were to determine the relationship between ultrasound attenuation and lint cleaner waste density, it was decided that a static measurement could produce the best results. The device selected, shown in Figure 2, used two commercially available piezoelectric transducers (Airmar Technology Corporation, Model AT-120) to convert the excitation voltage into pressure waves and vice versa. These transducers produced a narrow beam pattern with a small bandwidth to reduce interference effects; plots of the transducers' beam directivity and frequency response are depicted in Figure 3. Two adjustable casings were constructed for the transducers to facilitate directional tuning of up to 15 degrees. These were made from ultra-high molecular weight (UHMW) plastic tubing, which housed the transducers via rubber o-rings; the o-rings decoupled any high frequency structural vibration. Two aluminum blocks were used to support the transducer casings and provided for aiming adjustments in the x and y directions; magnets were used to prevent any accidental movement of these blocks. In order to secure the magnets with setscrews, a rectangular slot was machined into each block. A third block was constructed to support the lint cleaner waste samples, as well as eliminate any stray ultrasound reflection. In order to simplify sample preparation, a PVC tube was constructed to hold each sample (see Figure 2). Finally, a shallow rectangular recess was cut into the supporting steel plate to serve as a guide for the placement of the sample block.

After completion of the transmission measurement apparatus, the excitation and signal amplification circuitry for the transducers was designed and constructed according to the manufacturer's recommendations. In order to minimize internal heating of the transmitter, a monolithic timing circuit (Texas Instruments, TLC556) and a step-up transformer (*n=40*) were used to produce short excitation pulses. These pulses were generated for a duration of 5 ms at a frequency of 10 Hz. To amplify the transmitted energy collected by the receiver, a low noise operational amplifier (National Semiconductor, LM837) was used. The amplified signal was then sampled with an 866 MHz personal computer (Dell Computer Corporation, Dimension XPS T800r) and a 1.25 MS/s data acquisition board (National Instruments, PCI-MIO-16E-1) at a frequency of 840 kHz, almost four times the ultrasound frequency of 120 kHz. Because the ultrasound was received in short pulses, a trigger was used to activate the data acquisition in order to eliminate unneeded samples. This also freed up the processor for the computation of the root mean square (RMS) voltage, which was used as the measure of ultrasound transmission and was calculated according to the following equation.

$$v_{RMS} = \frac{1}{M}\frac{1}{N}\sum_{i=1}^{M}\sum_{n=1}^{N}\sqrt{\left(x_i[n]\right)^2} \qquad (2)$$

M is the total number of pulses, N is the total number of samples per pulse and $x_i[n]$ is defined to be the discrete sample n of pulse i. For this experiment, 100 pulses and 168 samples per pulse were acquired.

A simple test was used to verify that ultrasound transmission did not change as the excitation and amplification circuitry temperature increased. For this test, all electronic circuitry was placed inside the environmental control chamber at the Cotton Ginning Research Unit in Stoneville, Mississippi while the transducers remained outside the chamber. The transmission change was recorded as the temperature inside the chamber was increased from 60 to120 degrees Fahrenheit; a small, but inconsequential, increase in RMS voltage was observed.

Another test was used to eliminate the possibility of erroneous conclusions caused by transducer temperature fluctuation. In this test, the transducers were allowed to acclimate overnight to approximately 60 degrees Fahrenheit. Both transducers were then placed inside the conditioning chamber, which had been adjusted to 120 degrees Fahrenheit. The ultrasound transmission loss was then quickly measured. Subsequent measurements were taken every 15 minutes for one hour to evaluate any change. A slight reduction in the RMS voltage was observed, but it was believed inconsequential.

Experiment 1

Once the initial hardware testing was complete an experiment was designed and conducted in order to develop a relationship between ultrasound attenuation, lint cotton density, temperature and relative humidity. For this experiment, seven different amounts (0.01, 0.05, 0.1, 0.2, 0.3, 0.4, and 0.5 grams) of Shirley-analyzed lint cotton were used to simulate lint cleaner waste samples of different densities. Shirley-analyzed lint was selected in order to eliminate any effects associated with the motes, sticks or leaf particles. Each sample was prepared by rolling lint cotton, of the appropriate mass, into a cylindrical batt; weights were measured with an electronic balance (Sartorius Corporation, A120S-FW). The sample was then placed in the PVC sample tube (see Figure 2) and manipulated to occupy approximately the same volume (33.3 cm^3 or 2.03 in^3) yielding densities of 0.0003, 0.0015, 0.0030, 0.0060, 0.0090, 0.0120 and 0.0150 g/cm^3. The experiment was conducted in the environmental control chamber, which allowed for the selection of four different temperatures (60, 80, 100 and 120 degrees Fahrenheit) and three relative humidity levels (50, 70 and 90 percent). A completely randomized design was used to assign each combination of density, temperature and relative humidity. Each combination was replicated twice yielding 168 observations. After each sample was prepared, the ultrasound transmission (RMS voltage) was recorded according to the procedure described earlier.

Experiment 2

In order to complete the primary objective of this research, a second experiment was conducted to develop the relationship between trash components and ultrasound attenuation. Since lint cleaner waste is composed of more than lint cotton, this experiment was necessary to understand how specific trash components, such as mote trash or leaf and stick trash (also referred to as leaf/stick trash), affected ultrasound transmission. To prepare for this experiment, 'simulated' lint cleaner waste samples were created from known amounts of trash and lint cotton to produce four levels of trash (0.0667, 0.1, 0.15 and 0.2333 grams). Each waste sample contained 0.1 grams of Shirley-analyzed lint cotton and one of two possible trash components, mote trash or leaf/stick trash. The electronic balance, described earlier, was used to weigh each sample and a completely randomized design was employed to assign each sample's trash type and level. Each treatment was replicated 5 times for a total of 40 observations. Prior to each observation, the appropriate waste sample was placed in the PVC sample tube and manipulated to occupy approximately the same volume (33.3 cm^3 or 2.03 in^3). To eliminate any temperature effects, the experiment was conducted in the environmental control chamber. The ultrasound transmission was measured for each observation by recording the RMS voltage according to the same procedure used in Experiment 1.

Results

Using the data that was collected during the first experiment, an analysis of variance was performed in order to develop a correlation between lint cotton density, temperature, relative humidity and ultrasound transmission. Because transmission was dependent upon lint cotton density, the analysis of each variable's significance was performed with RMS voltage as the dependent variable. A preliminary evaluation of the data indicated that the relationships between temperature, lint cotton density, and ultrasound transmission were nonlinear. As a result, quadratic and cubic terms were included in the analysis of variance. The overall F test was significant (F=483.52, p<0.0001), indicating that the model, as a whole, accounted for a significant amount of the variation in voltage. Therefore, it was appropriate to proceed with testing variable effects. To test the different effects, the individual significance was evaluated for each effect; terms that were insignificant at the 0.05 level were removed from the model. From the analysis, it was determined that relative humidity did not have a significant affect ($F=1.25$) on ultrasound transmission. These results supported earlier work by D.P. Massa in which he indicated that humidity effects are only important at frequencies higher than 120 kHz (Massa, 1986). However, temperature and lint cotton density effects could not be eliminated from the model and actually accounted for 98 percent of the variation in voltage ($r^2=0.977$). This indicated that a temperature compensation scheme could be used to correct for transmission changes caused by temperature fluctuation. The equation presented below summarizes the analysis results (see Figure 4 for a graphical representation).

$$v_{RMS} = 2.89182 - (0.01468 + 1.17783d_l - 86.63386d_l^2)T + 0.0000411T^2 + 70.83516d_l - 19740.98d_l^2 + 529934.4d_l^3 \quad (3)$$

where d_l = mass density of lint cotton (g/cm^3)
T = temperature (Fahrenheit)
v_{RMS} = RMS voltage

A similar statistical analysis was performed on the data collected during the second experiment. RMS voltage was again treated as the dependent variable while trash type, temperature and amount of trash (mass) were treated as independent variables. The overall F test, was significant (F=25.26, p<0.0001), so the individual significance of each effect was evaluated at the 0.05 level. Temperature was quickly proven insignificant ($F=0.05$), which indicated that any temperature fluctuation during the test did not significantly affect the ultrasound transmission. Alternatively, the other independent variables: type of trash and trash mass, could not be eliminated from the model and accounted for 88 percent of the variation ($r^2=0.877$). The resulting regression equations are presented below.

$$v_{RMS} = 2.302225 - 1.224676(m_t) \quad \text{Leaf/stick trash} \quad (4)$$
$$v_{RMS} = 2.263578 - 2.431086(m_t) \quad \text{Mote trash} \quad (5)$$

In the equations, m_t is defined to be the trash mass (grams). A graphical representation of the regression equations and the recorded transmission levels are presented in Figure 5.

Conclusions

Research indicated that there was a significant relationship between ultrasound attenuation and lint cleaner waste density. However, this relationship was dependent upon waste constituents. To demonstrate these findings, an ultrasound attenuation plot is presented in Figure 6. This plot depicts the relationship between lint cleaner waste density and ultrasound attenuation. From the plot, it is obvious that the attenuation was much higher for lint cotton than mote trash or leaf/stick trash. Similarly, the mote trash attenuated more ultrasound than the leaf/stick trash. Thus, changes in the constituents of lint cleaner waste could severely degrade the performance of an ultrasonic mass flow sensing device. This research also supported the hypothesis that air temperature variation produced a substantial change in ultrasound transmission. As a result, an ultrasonic mass flow sensing apparatus, operating at a frequency of 120 kHz, must include a temperature compensation scheme.

Future work will include the evaluation of lower frequency ultrasonic transducers (< 120 kHz), in conjunction with the transducers discussed in this paper, for the measurement of waste constituents.

Disclaimer

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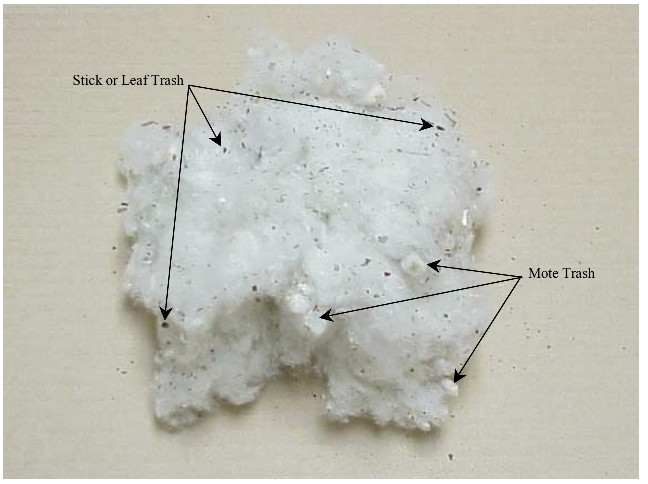

Figure 1. Lint cleaner waste.

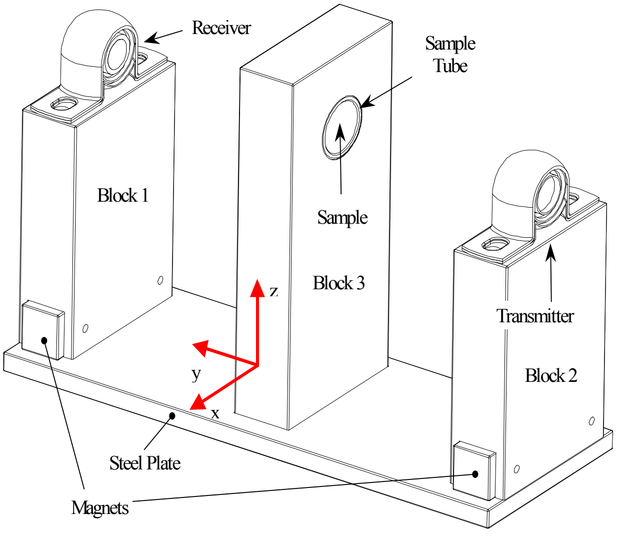

Figure 2. Ultrasound Transmission Measurement Apparatus.

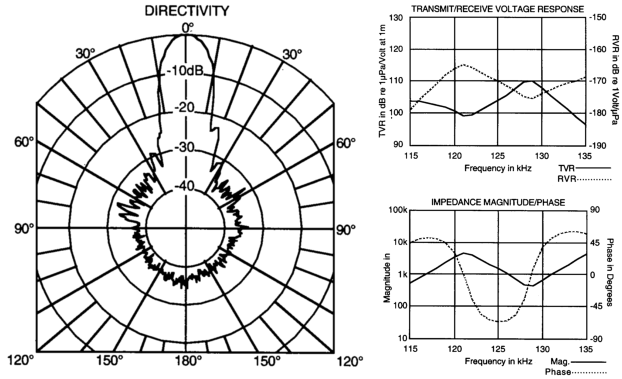

Figure 3. Ultrasonic transducer beam directivity and frequency response. (*Courtesy of Airmar Technology Corporation*)

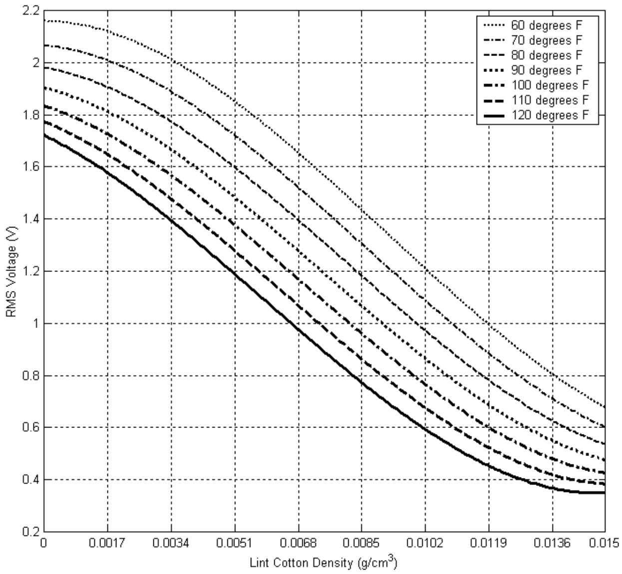

Figure 4. Ultrasound transmission (voltage) versus lint cotton density for various temperatures.

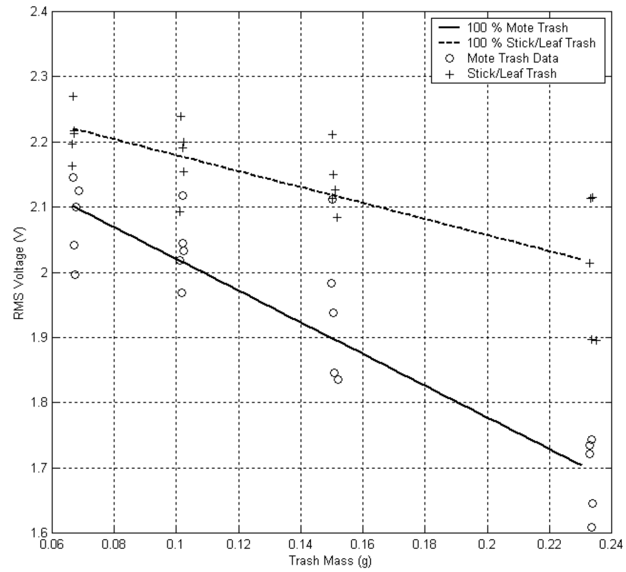

Figure 5. Relationship between RMS voltage (ultrasound transmission) and trash constituents.

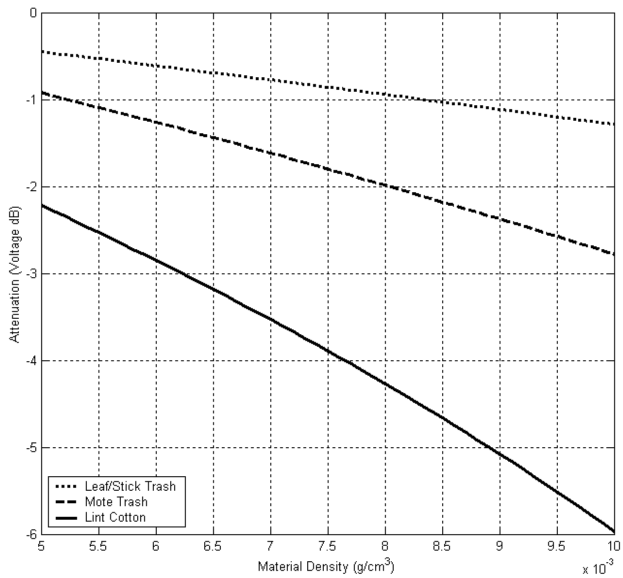

Figure 6. Comparison between ultrasound attenuation for lint cotton, lint with mote trash and lint with stick or leaf trash.