Experimental Study of Sound Travel-Time Estimation Method in Stored Grain

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Abstract—**One common and traditional method for detecting stored grain deterioration is to measure grain temperature by contact sensors. Many sensors are installed throughout the bin for this. Temperature maps can also be obtained using acoustic travel-time tomography, which would be more suitable for store grain due to its non-contact measurement. The measurement of sound travel-time in grain bulk was researched. A time-delay estimation method using triple correlation with wavelet transform is proposed for solving the problem of sound attenuation in grain bulk. A measurement system of sound travel-time based on virtual instrument was built. Sound travel-time in soybeans was measured by the proposed method, cross-correlation method, and cross-correlation with wavelet transform method. The results show that the proposed method is best in measurement stability and accuracy. Thus it is expected to be used in an actual acoustic temperature monitoring system for stored grain.**

Index Terms—**acoustic tomography; temperature measurement; stored grain; sound travel-time estimation; correlation; wavelet transform**

I. INTRODUCTION

Stored grain is destroyed by fungi, insects and moisture. That could be reflected by temperature of grain [1]. High temperature zone in a grain bulk which called a hot spot is the location of spoilage occurred. Grain is a poor conductor of heat. Temperature monitors must have a higher space resolution for detecting hot spot earlier. Currently, temperature measurement of stored grain is usually realized by contact method. Some cables which embed contact temperature sensors are installed throughout the silo [2]. Normally, the distance between two sensors in the cable is 1.5~3m; about 5 cables should be installed when the diameter of silo is 6~8m. As a consequence of contact method, the space resolution of temperature measurement is low, and a hot spot can’t be detected when it exists far away from any of the temperature sensors. If the spoilage in a small area of grain can’t be detected in time, losses of grain will be much higher. Compared with contact methods, non-contact methods would be much better for stored grain temperature monitoring [2].

Temperature maps can be obtained using acoustic travel-time tomography. It is based on the measurements of travel-time values between a sound source and a receiver. A combination of measurements along different sound propagation paths within an area or volume under investigation and the use of tomographic techniques enable one to draw conclusions on the spatial distribution of temperature within a certain volume or area [3]. Acoustic temperature measurement [3-7] has many advantages such as non-contact, wide temperature range, suitable for large volume or area, easy maintenance and so on. It has already been applied on temperature measurement of the industry furnace. For using the method, several sound transmitters/receivers are installed around the measured area. After sound travel-time of each sound path is measured, average temperature for each sound path can be calculated, and the temperature field can be reconstructed by an appropriate reconstruction algorithm.

Stored grain can be considered as a porous medium. In stored grain, sound is transmitted principally through the gas in the narrow passageways between the grain kernels [8,9]. Therefore, the temperature distribution of stored grain could be monitored by acoustic tomography.

Sound travel-time measured accurately is very important for acoustic temperature measurement in stored grain. As a consequence of acoustic reflection and viscosity caused by grain kernels, the sound attenuation related to frequency obviously occur during the propagation in grain bulk [8,9]. For example, a sound at 500Hz is attenuated 70% after propagating 1m in soybeans, and the figure can be increased to 90% as the frequency is 2000Hz. It makes the sound signal distorted that increases the difficulty to measure the sound travel-time accurately in stored grain.

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In this paper, a time-delay estimation method using triple correlation with wavelet transform was proposed. A measurement system of sound travel-time in stored grain based on the virtual instrument was built. Sound travel-time in soybeans was measured by the proposed method, cross-correlation method, and cross-correlation with wavelet transform method. The stability and accuracy of three methods were compared by experimental data.

II. THEORY OF SOUND TRAVEL-TIME MEASUREMENT IN STORED GRAIN

The velocity of sound in a gas is related to gas temperature by the equation [6,7]

$$c = \sqrt{\frac{\gamma R T}{M}} \ . \tag{1}$$

where c is the adiabatic speed of sound, γ is the ratio between the specific heats at constant pressure and volume of the gas, R is the gas constant; M is the molecular weight of the gas, and T is the temperature of the gas. As the expression $Z = \sqrt{\gamma R / M}$ is conventional, the equation (1) could be expressed as

$$c = Z\sqrt{T} \ . \tag{2}$$

where Z is the acoustic constant determined by the composition of the gas, it is about 20.045 for air.

Usually, if sound travel time t from location A to location B is measured, average temperature T along the sound propagation path can be calculated by the equation

$$T = \left(\frac{l}{t \cdot Z}\right)^2 \ . \tag{3}$$

where l is the distance between A and B.

In stored grain, sound propagates principally through the gas between the grain kernels. For making equation (3) available in stored grain, a parameter λ called grain porosity influence factor is introduced in the paper. And equation (3) could be changed as follow

$$T = \left(\frac{l \cdot \lambda}{t \cdot z}\right)^2 \ . \tag{4}$$

λ is affected by sound frequency, composition of the gas and the average spacing between the grain kernels. When sound frequency and composition of gas are fixed, λ principally depend on average spacing between the grain kernels. In the shallow region of grain bulk, because of the weight of grain load, the average spacing is getting small with the increase of the depth of grain bulk, λ is also changed in different depth of grain bulk. If the depth is more than 0.5m, the average spacing will be not changed with the increase of the depth of grain bulk, and λ could be considered as invariant. The value of λ can be obtained by experimental calibration in practice. Equation (4) is the model of acoustic temperature measurement in stored grain, the factors affecting λ and its solving method will be discussed in another paper.

Supposing, t_1 and t_2 are sound travel-time between location A and B measured respectively at two different temperatures T_1 and T_2 of stored grain. With equation (4), we can have equation as follow

$$\frac{t_2}{t_1} = \sqrt{\frac{T_1}{T_2}} \ . \tag{5}$$

Using equation (5), the stability and accuracy of sound travel-time measurement could be evaluated easily without experimental calibration of λ.

III. THE SYSTEM OF SOUND TRAVEL-TIME MEASUREMENT

For researching the method of sound travel time measurement in stored grain, a system of sound travel time measurement based on the virtual instrument was built as shown in Figure 1.

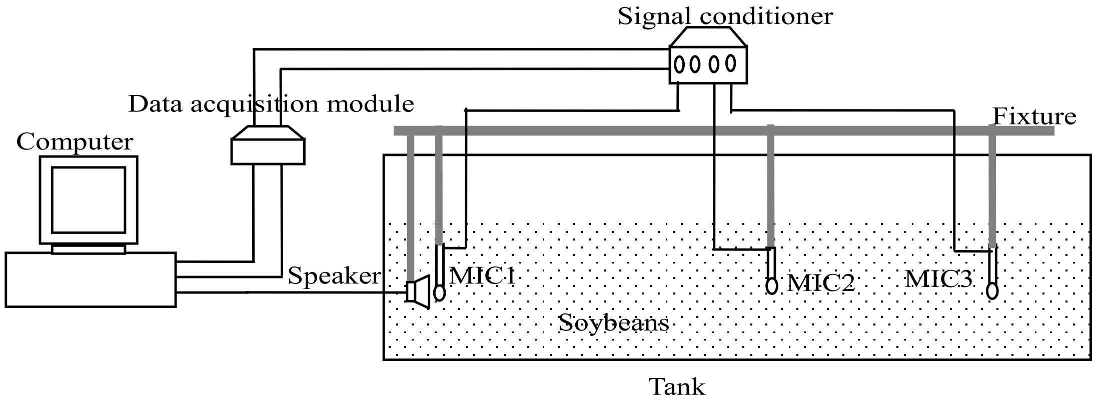


Figure 1. System of sound travel time measurement.

The system includes a cubic tank (2m×0.6m× 0.6m) filled with soybeans, a signal conditioner, a data acquisition module, a computer installed LabVIEW, a fixture made to hold, a speaker and three microphones with preamplifiers (MIC1~MIC3). The distance between the speaker and MIC1, MIC1 and MIC2, MIC1 and

MIC3 are 0.08m, 1.2m and 1.8m respectively. The signal conditioner is used to supply power for MIC1~MIC3, magnify and filter the signals from MIC1~MIC3. The data acquisition module is used to collect signals from MIC1, MIC2 and MIC3 simultaneously. The sampling frequency is 100kHz, and the sample number of each channel is 30000.

Based on virtual instrument technology, the function of the system could be customized easily, for example, changing sound waveform and its parameters, adding various methods of sound travel-time measurement, and so on. LabVIEW is chosen as the software platform for several reasons. It is a graphical rather than a text based programming language such as C or Fortran, allowing faster development. Another argument is the fast execution of the complied code (comparable to C-code). Finally the program easily integrates with existing hardware and/or external code [10].

In the paper, a band-limited chirp signal is used as the acoustic signal for ensuring stability of sound travel time measurement. The grain acts as a low-pass filter for acoustic signal. If the sound frequency is too high, the sound attenuation is serious; but if the sound frequency is too low, the influence of sound frequency on sound velocity can't be neglected. Therefore, a 200~1500Hz chirp signal is available based on above analysis and actual experiment.

IV. TIME-DELAY ESTIMATION METHOD USING TRIPLE CORRELATION WITH WAVELET DE-NOISE

Time-delay estimation is an important signal processing problem and has received significant amount of attentions during past decades in various applications, including radar, sonar, radio navigation, wireless communication, acoustic tomography, etc [11].

A. Cross-Correlation (CC)

Supposing $x_1(n)$ and $x_2(n)$ are the signals measured in location A and B respectively, and they can be written in the form

$$\begin{aligned} x_1(n) &= s(n) + n_1(n) \\ x_2(n) &= \alpha \cdot s(n-D) + n_2(n)\ . \end{aligned} \tag{6}$$

where $s(n)$ is the useful signal, D is the time-delay of signal transmitted from A to B, $n_1(n)$ and $n_2(n)$ are additive noise, α is the attenuation factor of signal.

The cross-correlation [12] of $x_1(n)$ and $x_2(n)$ can expressed as

$$\begin{aligned} R_{x_1x_2}(m) &= E\left[x_1(n)x_2(n+m)\right] \\ &= E\left[\left(s(n)+n_1(n)\right)\left(\alpha\cdot s(n+m-D)+n_2(n+m)\right)\right] \\ &= \alpha\cdot R_{ss}(m-D)+\alpha\cdot R_{n_1s}(m-D)+R_{sn_2}(m)+R_{n_1n_2}(m)\ . \end{aligned} \tag{7}$$

According to the properties of auto-correlation, it can be known that $|R_{ss}(m\text{-}D)|\le R_{ss}(0)$. Suppose $n_1(n)$ and $n_2(n)$ are the white Gaussian noise without correlation between them, and there is also no correlation between signal and noise, then $R_{n_1s}(\cdot)$, $R_{sn_2}(\cdot)$ and $R_{n_1n_2}(\cdot)$ are equal to 0. Both $R_{ss}(\cdot)$ and $R_{x_1x_2}(\cdot)$ can obtain the maximum as $m=D$. And $m=D$, $R_{x_1x_2}(D)=\max[R_{x_1x_2}(m)]$ is the time-delay estimation between $x_1(n)$ and $x_2(n)$ with cross-correlation method.

B. Cross-Correlation with Wavelet Transform (WT-CC)

In fact, the noise usually isn't the perfect white Gaussian noise and may be correlative, the observation interval of signal isn't long enough either, so $R_{n_1s}(\cdot)$, $R_{sn_2}(\cdot)$ and $R_{n_1n_2}(\cdot)$ are not equal to 0 strictly. If the signal-to-noise ratio (SNR) is too low, the maximum of $R_{x_1x_2}(m)$ could not be obtained at $m=D$. That will decrease the accuracy of time-delay estimation. Therefore, in this paper, Mallat decomposition and reconstruction algorithm of wavelet transform is used to de-noise the signal of $x_1(n)$ and $x_2(n)$.

Using the wavelet transform, a signal can be decomposed, layer by layer, into approximation coefficients and detail coefficients. The general de-noising process can be divided into following three steps.

(1) Selecting a proper wavelet mother function. When decomposing one-dimensional digital signal with wavelet transform, the wavelet function of db$N$ wavelet series is usually used as mother function. Positive integer N is the sequence number of wavelet function. In this paper, db18 is chosen as the wavelet mother function based on experiment analyses.

(2) Selecting the scale of decomposition j. The characteristic of the Mallat decomposition algorithm is separating high frequency section from the low frequency coefficient in each scale. The method is useful for preliminary separating high frequency noise from the low frequency signal. If the bandwidth of sampling signal is f_k, after Mallat decomposition in the scale of j, the low frequency coefficient of signal $a_k^{(j)}$ is obtained, and the range of bandwidth of $a_k^{(j)}$ is $0\sim f_k/2^j$ [13]. Therefore, if the upper limit of available bandwidth of signal is f, the scale j must be appropriate to make $f_k/2^j$ approached to f. That will be made $a_k^{(j)}$ include the whole available information of signal, and put the noise into the high frequency coefficient of signal $d_k^{(j)}$ in each scale as much as possible. In this paper, the sampling frequency of the system was 100kHz, according to Nyquist sampling theory, the bandwidth of sampling signal f_k is equal to 50kHz. Decomposing $x_1(n)$ and $x_2(n)$ in the scale of j=5, the range of bandwidth of $a_k^{(5)}$ is 0~1562.5Hz, that is suitable for 200-1500Hz chirp signal.

(3) Signal de-noise and reconstruction. Since $a_k^{(j)}$ include the whole available information of signal, the constraint de-noise method can be used to eliminate signal noise. That is, high frequency coefficient of signal d_k in all scale is set to 0, then reconstruct $a_k^{(j)}$ with the Mallat reconstruction algorithm (inverse of Mallat decomposition) to generate de-noise signals $x'_1(n)$ and $x'_2(n)$.

The cross-correlation of $x'_1(n)$ and $x'_2(n)$ can be expressed as follows.

$$
\begin{aligned}
&R_{x'_1x'_2}(m)=E\left[x'_1(n)x'_2(n+m)\right]\\
&=E\left[\left(s'(n)+n'_1(n)\right)\left(\alpha\cdot s'(n+m-D)+n'_2(n+m)\right)\right] \qquad (8)\\
&=\alpha\cdot R_{s's'}(m-D)+\alpha\cdot R_{n'_1s'}(m-D)+R_{s'n'_2}(m)+R_{n'_1n'_2}(m)\ .
\end{aligned}
$$

According to the properties of auto-correlation, it can be known that $|R_{s's'}(m-D)|\le|R_{s's'}(0)|$. And m=D, $R_{x'_1x'_2}(D)=\max[R_{x'_1x'_2}(m)]$ is the time-delay between $x_1(n)$ and $x_2(n)$ estimated by cross-correlation with wavelet transform. Due to de-noising the signal by wavelet transform, SNR is increased, so the stability and accuracy of time-delay estimation can be better than cross-correlation.

C. *Triple Correlation with Wavelet Transform (WT-TC)*

The triple correlation with wavelet transform is proposed for improving the stability and accuracy of time-delay estimation in stored grain.

The auto-correlation [14] of de-noising signal $x'_1(n)$ is expressed as

$$
\begin{aligned}
&R_{x'_1x'_1}(m)=E\left[x'_1(n)x'_1(n+m)\right]\\
&=E\left[\left(s'(n)+n'_1(n)\right)\left(s'(n+m)+n'_1(n+m)\right)\right] \qquad (9)\\
&=R_{s's'}(m)+R_{n'_1s'}(m)+R_{s'n'_1}(m)+R_{n'_1n'_1}(m)\ .
\end{aligned}
$$

In the equation (8) and (9), $R_{s's'}(\bullet)$ can be considered as the useful signal, and the others can be considered as the noise. For simplifying the calculation, new expression is given as follows.

$$
\begin{aligned}
&y_1(m)=R_{x'_1x'_1}(m)=R_{s's'}(m)+\omega_1(m)\\
&y_2(m)=R_{x'_1x'_2}(m)=\alpha R_{s's'}(m-D)+\omega_2(m)\ .
\end{aligned}
\qquad (10)
$$

From equation (10), it can be seen that, the useful signal of $y_2(m)$ is the delay and attenuation of the useful signal of $y_1(m)$, and the time-delay between them is also equal to D. The cross-correlation of $y_1(m)$ and $y_2(m)$ can be expressed as

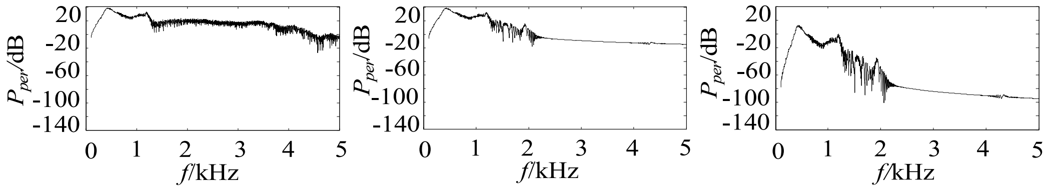
$$
\begin{aligned}
&R_{y_1y_2}(\tau)=E\left[y_1(m)y_2(m+\tau)\right]\\
&=E\left[\left(R_{s's'}(m)+\omega_1(m)\right)\left(\alpha\cdot R_{s's'}(m-D+\tau)+\omega_2(m+\tau)\right)\right] \qquad (11)\\
&=\alpha\cdot R_{RR}(\tau-D)+\alpha\cdot R_{\omega_1R}(\tau-D)+R_{R\omega_2}(\tau)+R_{\omega_1\omega_2}(\tau)\ .
\end{aligned}
$$

In the equation (11), $R_{RR}(\cdot)$ is the auto-correlation of $R_{s's'}(\cdot)$ which is time function obtained by auto-correlation of useful de-noise signal $s'(n)$, so we have $|R_{RR}(\tau\text{-}D)|\le|R_{RR}(0)|$. And τ=D, $R_{RR}(D)=\max[R_{RR}(m)]$ is the time-delay of $x_1(m)$ and $x_2(m)$ estimated by triple correlation with wavelet transform. Even though the noise isn't the perfect white Gaussian noise or the observation interval of signal isn't enough, the correlation between signal and its self is obviously stronger than that between signal and noise (also stronger than the correlation between noises). Therefore, the SNR of $y_1(m)$ and $y_2(m)$ is much better than $x'_1(n)$ and $x'_2(n)$. Compared with WT-CC and CC, WT-TC could be better in stability and accuracy for time-delay estimation.

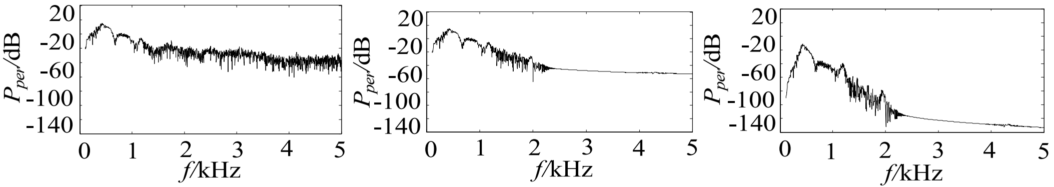
V. EXPERIMENT OF SOUND TRAVEL-TIME ESTIMATION IN STORED GRAIN

During the experiment, MIC1 is 0.08m away from speaker, the distance l between MIC1 and MIC2 is 1.2m, and that is 1.8m between MIC1 and MIC3. Fill the tank with soybeans at three times, make the depth h of microphone in soybeans be 0.3m, 0.4m and 0.5m respectively, and in this way six sound paths are obtained. The travel-times along these six paths can be estimated from the signals received simultaneously by MIC1, MIC2 and MIC3. For each sound path, three travel-time estimation methods, that is, CC, WT-CC and WT-TC described in section IV are used.

A group of power spectrum density (PSD) of measured signal at the sound path of h=0.5m, l=1.8m is shown in Figure 2. The power spectrum density is estimated by periodgram method. $x_1(n)$ and $x_2(n)$ are measured signal of MIC1 and MIC3.



(a) PSD of signal $x_1(n)$ (b) PSD of de-noise signal $x'_1(n)$ (c) PSD of signal $y_1(m)$



(d) PSD of signal $x_2(n)$ (e) PSD of de-noise signal $x'_2(n)$ (f) PSD of signal $y_2(m)$

Figure 2. PSD of measured signals.

Following can be seen from Figure 2.

(1) After propagating for a distance, the sound signal is obviously attenuated, the higher the frequency is, and the more the sound signal attenuates.

(2) After wavelet transform de-noising, the signal component with frequency higher than 1500Hz is attenuated about 20dB, and its PSD curve becomes smooth, but the attenuation of the signal component with frequency lower than 1500Hz is not obvious.

(3) Both $y_1(m)$ and $y_2(m)$ are attenuated 70dB based on de-noise signal $x'_1(n)$ and $x'_2(n)$ as the frequency higher than 1500Hz, nevertheless, only 20~30dB attenuation as the frequency lower than 1500Hz. Therefore, it is concluded that the SNR could be increased much more after wavelet transform de-noise and correlation.

The temperature change in stored grain is very slow. So measuring sound travel-time of the same path for many times and getting average value of them can improve the stability and accuracy of time-delay estimation effectively.

Coefficient of variance is the ratio of standard deviation and average of data. Small value of the coefficient of variance reflects the good stability of data. Measure the sound travel-time of each sound path in stored grain for N times, and its coefficient of variance v can be expressed as

$$v = \frac{s}{\bar{t}} \times 100\% \,, \quad s = \sqrt{\frac{\sum_{i=1}^{N}(t_i - \bar{t})}{N-1}} \,, \quad \bar{t} = \frac{\sum_{i=1}^{N} t_i}{N} \,. \quad (12)$$

where s is the standard deviation of measured sound travel-time; $\bar{t}$ is the average value of sound travel-time measured for N times; t_i is the sound travel-time at the ith estimation.

As the temperature of soybeans was T_1=300K and T_2=291K respectively, three sound travel-time estimation methods were used to measure sound travel-time of six sound paths in stored grain for 100 times. $\bar{t_1}$ and $\bar{t_2}$ are the average values of measured data at different temperature of stored grain. Equation (5) can be used to evaluate the accuracy of three methods, it expressed as

$$r = \sqrt{\frac{T_1}{T_2}} = \sqrt{\frac{300\text{K}}{291\text{K}}} = 1.0153 \,. \quad (13)$$

$$r_m = \frac{\bar{t_2}}{\bar{t_1}} \,. \quad (14)$$

And the relatively error of the ratio of sound travel-time at different temperature in stored grain can be calculated as follow

$$r_e = \frac{|r_m - r|}{r} \times 100\% \,. \quad (15)$$

In the paper, the coefficient of variance v and the relatively error of the ratio of sound travel-time re are used to evaluate stability and accuracy of above three sound travel-time estimation methods, shown in TABLE I. v_1 and v_2 are the coefficient of variance of sound travel-time measured at temperature of 300K and 291K in stored grain.

TABLE I. THE STABILITY AND ACCURACY OF THREE SOUND TRAVEL-TIME ESTIMATION METHODS.

Sound paths in stored grain	CC			WT-CC			WT-TC		
	v_1(%)	v_2(%)	r_e(%)	v_1(%)	v_2(%)	r_e(%)	v_1(%)	v_2(%)	r_e(%)
l=1.2m,h=0.3m	0.25	0.18	0.17	0.25	0.19	0.35	0.09	0.06	0.12
l=1.8m,h=0.3m	0.32	0.19	0.09	0.22	0.13	0.11	0.07	0.03	0.13
l=1.2m,h=0.4m	0.27	0.31	0.64	0.20	0.21	0.23	0.10	0.08	0.05
l=1.8m,h=0.4m	0.08	0.12	0.01	0.07	0.11	0.02	0.01	0.01	0.07
l=1.2m,h=0.5m	0.11	0.08	0.12	0.10	0.07	0.02	0.09	0.03	0.16
l=1.8m,h=0.5m	0.07	0.01	0.05	0.07	0.03	0.09	0.06	0.02	0.02
Average	0.183	0.148	0.180	0.152	0.123	0.137	0.070	0.038	0.092

From TABLE I, it can be seen that, both stability and accuracy of WT-TC are much better than the other two methods. The maximum of re of WT-TC, WT-CC and CC are 0.16%, 0.35% and 0.64% respectively.

According to equation (13) and (14), if T_2 (or T_1) is known, T_1 (or T_2) can be calculated. Supposing that T_1=300K is already known, the ratio of sound travel-time r_m measured by three methods, the T_2 calculated by equation (13) and (14), and its absolute error T_e=|T_2-291K| are shown in TABLE II. It can be seen that, the maximum errors of T_2 calculated by the r_m of WT-TC, WT-CC and CC are 0.93K, 2.15K and 3.86K respectively, and the absolute errors of T_2 calculated by the r_m of WT-TC in six sound paths are all less than 1K.

VI. CONCLUSION

One common and traditional method for detecting stored grain deterioration is to measure grain temperature by contact sensors. Temperature maps can also be obtained using acoustic travel-time tomography, which would be more suitable for store grain due to its non-contact measurement. The key to acoustic temperature measurement is to measure sound travel-time accurately. In grain bulk, sound is attenuated obviously as the sound frequency and propagating distance increasing, which makes it very difficulty to measure sound travel-time in grain accurately. To solve this problem, a time-delay estimation method using triple correlation with wavelet transform (in short WT-TC) is proposed; an appropriate sound waveform and its parameters are selected with care; and a measurement system of sound travel-time based on virtual instrument is built. Sound travel-times in soybeans along six different paths were measured by the proposed WT-TC method, cross-correlation (CC) method, and cross-correlation with wavelet transform (WT-CC) method. The experiment results show that both wavelet transform de-noise and multiple correlation can improve the SNR of signals effectively, as a consequence, the stability and accuracy of WT-TC are much better than WT-CC and CC for sound travel-time estimation in soybeans. Therefore, WT-TC is expected to use in an actual acoustic temperature monitoring system for stored grain.

TABLE II. THE CALCULATED T_2 AND ITS ABSOLUTE ERROR AS THE T_1 IS 300K.

Sound paths in stored grain	CC			WT-CC			WT-TC		
	r_m	T_2(K)	T_e(K)	r_m	T_2(K)	T_e(K)	r_m	T_2(K)	T_e(K)
l=1.2m,h=0.3m	1.0136	292.00	1.00	1.0116	293.15	2.15	1.0141	291.72	0.72
l=1.8m,h=0.3m	1.0144	291.54	0.54	1.0142	291.69	0.69	1.0140	291.77	0.77
l=1.2m,h=0.4m	1.0087	294.86	3.86	1.0130	292.35	1.35	1.0148	291.31	0.31
l=1.8m,h=0.4m	1.0152	291.08	0.08	1.0151	291.14	0.14	1.0146	291.43	0.43
l=1.2m,h=0.5m	1.0165	290.40	0.60	1.0155	290.91	0.09	1.0170	290.07	0.93
l=1.8m,h=0.5m	1.0158	290.74	0.26	1.0162	290.51	0.49	1.0155	290.91	0.09

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