High-Contrast RF Correlation Imaging of Defects in Food Package Seals

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Abstract - Previous research work to detect channel defect in package seals using pulse-echo ultrasound inspired the Backscattered Amplitude Integral (BAI) imaging and RF sample (RFS) imaging techniques. BAI-mode imaging detects subwavelength-sized channels as small as 6-μm, and reliably as small as 38-μm at 17.3 MHz. BAI images display the integral of the envelope-detected RF signal at each transducer position over a rectangular scan area. RFS-mode imaging uses a single time-sample to form the image and reliably detects channels as small as 15 μm, but requires *a priori* knowledge of the material and an approximate depth into the sample of the channel defect. The two former image formation techniques, as well as the newly proposed technique, are evaluated from the same acquired pulse-echo RF data set. All images are formed with a 17.3-MHz 6.35-mm-diameter focused ultrasound transducer (f/2, 173-μm –6 dB pulse-echo lateral beamwidth at the focus, λ=86 μm) scanned over a rectangular grid, keeping the package material in the focal region. All techniques are evaluated with the same set of laboratory-made channel defects: plastic and aluminum foil trilaminate film with 6-, 10-, 15-, 38- and 50-μm-diameter channels filled with water or air. The new RF correlation image technique is formed from the correlation coefficient of each RF echo signal relative to a reference signal that does not pass through a channel defect. Prior to processing, the acquired RF echo signals are first windowed to match within the sample the range where the two materials are bonded, that is, the range where channel defects occur. The statistical study on the laboratory-made channel defects shows that RF correlation technique has the highest detection rate relative to BAI-mode and RFS-mode image for 15-, 10- and 6-μm channel defects. It also is the most effective at smoothing the background, leading to the greatest Contrast-to-Noise (CNR) enhancement.

I. INTRODUCTION

An important part of the food packaging process is the detection of channel defects in the package's seal. Previous research has shown that channel defects in packaging seals can be detected using the Backscattered Amplitude Integral (BAI) imaging method [1]. Channels with diameters of 38-μm or larger can be detected reliably using this technique at a frequency of 17.3 MHz. However, at the same frequency, smaller channels (6-μm diameter) can be revealed by processing the same three-dimensional data set used in BAI-mode imaging according to RF sample (RFS) imaging technique [2]. RFS is computationally efficient, but needs significant information about the material and the approximate depth into the sample of the channel defect.

The contribution introduces a new technique that utilizes the normalized correlation coefficient that is generated by comparison to the RF echo signal from a normal (reference) sample region. Further, this new technique is compared against the BAI and RFS techniques.

II. DATA COLLECTION

The materials and data acquisition method are discussed extensively in [2,3]; therefore, these details will be mentioned only briefly. Two types of trilaminate packaging film are examined. The plastic trilaminate film is 110-μm thick with an average speed of sound of 2380 m/s. The aluminum foil trilaminate film is 120-μm thick with an average speed of sound of 2460 m/s.

Defects are created by fusing together two layers of film with a tungsten wire sandwiched in between and removing the wire after the seal is cooled. The channel sizes are 6-, 10-, 15-, 38-, and 50-μm. Defect sizes are confirmed using a light transmission microscope.

The three-dimensional data set is collected using a nominal 20-MHz focused transducer operating with an actual center frequency of 17.3 MHz (6.35 mm in diameter, f/2, 173-μm –6 dB pulse echo lateral beamwidth at the focus). The Panametrics transducer is shock-excited by a Panametrics 5800 pulse-receiver. The transducer is scanned in two directions. The surface of the packaging material is perpendicular to the beam axis and the sample is in the transducer's focus throughout the scan. The echo signal is captured by LeCroy digitizing oscilloscope with a sampling rate of 500 MHz, keeping 512 samples for each transducer position.

III. IMAGE FORMATION

Figure 1 shows a RF signal from a 6-μm ACP channel defect (see Table 1 for abbreviations). It is assumed that the first reflection from the front surface of the package has the greatest amplitude. The times t_1 and t_2 are relative to the front surface and are used to determine the correlation window time-gate for the RF correlation (RFC) image.

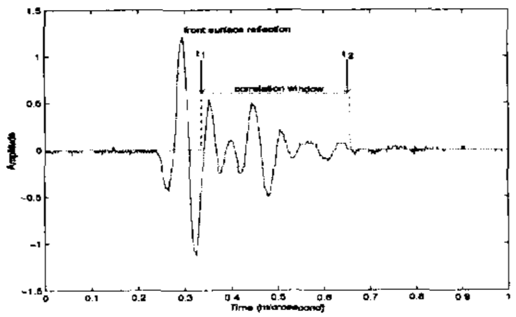

Figure 1. A 17.3-MHz RF signal with 6-μm ACP channel defect.

BAI-mode imaging

Every RF waveform is Hilbert-transformed, and the resulting envelope is integrated to obtain the BAI value for that transducer position [3].

RFS-mode imaging

RFS technique takes advantage of the fact that the first reflection from the front surface of package will have the greatest amplitude. The waveforms at each transducer position are time-normalized to correct for rough flaws in the front surface of the package, which would change the absolute time to the first reflection for each waveform. This normalization is accomplished by aligning the RF echo signal according to when the signal reaches its maximum. To create the RF sample image, a single sample of the time-justified waveform is kept [2].

RFC-mode imaging

A reference signal is chosen to represent the RF echo signal not intersecting a channel defect. Five RF signals away from the channel defect are averaged for the reference signal. Figure 2 shows an example of two difference signals. The dashed line is an RF signal intersecting the channel defect minus the reference signal and the solid line is an RF signal not intersecting the channel defect minus the reference signal. It is clear that the difference is larger for the RF signal that intersects the channel defect than the difference for the signal that does not intersect the channel defect.

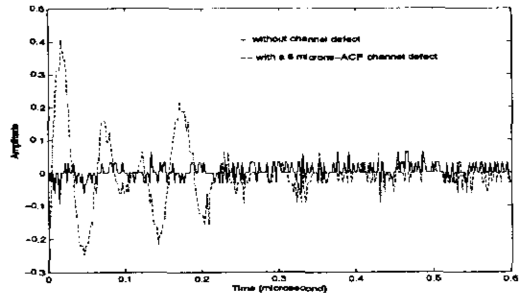

Figure 2 Difference of RF signals and reference signal in the correlation window for a 6-μm ACP channel defect.

After forming a reference signal, the normalized correlation coefficient between the reference signal and RF echo signal is calculated at each transducer position to determine the distance between the two ultrasound echoes. The RFC image is created by displaying the 2-D matrix of the normalized correlation coefficients.

In order to implement this technique, we choose the window where the correlation coefficient is calculated. In this work, the following two cases are studied:

1. The correlation window includes the entire RF-signal range starting from the front surface of the package material. This case is denoted as the RF correlation over the entire range (RFCE).
2. The correlation window includes only a short, specified time-gate of the RF signal. In this case, the correlation window is placed between t_1 and t_2 (Figure 1) for which a coarse estimation of the channel defect range is

required. This case is denoted as the RF correlation over the specified range (RFCS).

Performance Measures

Contrast is an important measurement for cyst detectability. Contrast-to-noise ratio (CNR), which includes the effect of speckle and noise, is a more complete description of detectability.

Local contrast is defined as $(S_b - S_c)/S_b$, where S_b is the mean value of the background image brightness and S_c is the mean value of the channel. This measure is useful for images that will be logarithmically compressed. The image contrast is defined as the mean value of the background minus the mean value of the channel divided by the total range in the image,

$$C = \frac{\frac{1}{N_b}\sum_i p_{b_i} - \frac{1}{N_c}\sum_i p_{c_i}}{\max_i p_i - \min_i p_i} \qquad (1)$$

where p_i represents an image pixel, N is the total number of pixels, and the subscribes b and c indicate pixels in the background or channel, respectively. To define CNR, the noise is defined as the standard deviation of the background pixels, σ_b. CNR is thus

$$CNR = \frac{C}{\sigma_b} \qquad (2)$$

Five spatially separated regions covering the background are used to calculate the mean pixel value and the corresponding standard deviation. Three spatially separated locations in the defect regions are used to calculate the mean pixel value in the defect.

IV. Results and Discussion

Four to eight data sets were collected for each combination of channel size, type of packaging film, and material in the channel.

Table I shows the detection rates for the BAI, RFS, RFCE and RFCS techniques. All four techniques reveal 100% of channels 38 µm or larger, regardless of the type of channel defect. From this table, the following conclusions can be drawn: (1) RFC imaging technique is not sensitive to correlation range for the larger channel defect, i.e., 38 µm and 50 µm. Both RFCE and RFCS achieve 100% detection. (2) RFC is very sensitive to the correlation range for the small channel, i.e., smaller than 15 µm. The smaller the channel size, the more sensitive the RFC technique is. For example, RFCS still achieves 50% and 100% of channel size 6 µm for WCA and ACA while RFCE achieves 0% detection for the same channel defect. Therefore, the appropriate choice of correlation window will play an important role in RFC technique. (3) BAI imaging performance varies greatly for small channel size (i.e., 6 µm, 10 µm and 15 µm). Although BAI mode imaging allows us to detect some channels as small as 6 µm, we can only detect reliably channels as small as 38 µm. (4) The detection rate for RFS imaging is comparable to the detection rate for RFCS. The RFS technique is slightly more likely than RFCS to miss a 10- or 15-µm-diameter channels, and slightly less likely than RFCS to miss a 6-µm channel.

Table I. Detection rates

Film	Channel Size (µm)	BAI	RFS	RFCE	RFCS
Plastic/Water (WCP)	50	5/5	5/5	5/5	5/5
	38	5/5	5/5	5/5	5/5
	15	2/7	3/7	4/7	5/7
	10	4/5	3/5	2/5	4/5
	6	1/4	¾	2/4	2/4
Plastic/Air (ACP)	50	5/5	5/5	5/5	5/5
	38	5/5	5/5	5/5	5/5
	15	6/6	6/6	6/6	6/6
	10	3/5	3/5	4/5	5/5
	6	1/4	¾	2/4	2/4
Foil/Water (WCA)	50	5/5	5/5	5/5	5/5
	38	5/5	5/5	5/5	5/5
	15	3/5	4/5	3/5	5/5
	10	0/6	5/6	1/6	4/6
	6	3/4	4/4	0/4	2/4
Foil/Water (ACA)	50	5/5	5/5	5/5	5/5
	38	5/5	5/5	5/5	5/5
	15	2/8	7/8	4/8	8/8
	10	4/5	4/5	1/5	5/5
	6	4/4	4/4	0/4	4/4

Figure 3 shows images created with each image-formation technique. The defect is a 6-µm air-filled channel in plastic trilaminate film. The defect is detected in the RFS and RFCS images, (b) and (d). The RFS image has greater contrast, and the RFCS image has the smoother background.

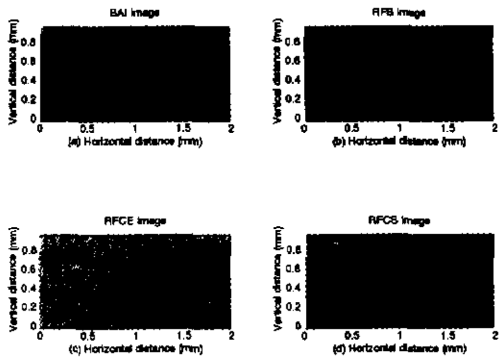

Figure 3. Processed images for a 6-μm ACP channel defect. (a) BAI (b) RFS, 0.082 μs (c) RFCS and (d) RFCS, $t_1 = 0.08\,\mu s$ and $t_2 = 0.12\,\mu s$

The contrast (Equation 1) versus channel size and CNR (Equation 2) versus channel size for air-filled channels in plastic trilaminate film are shown in Figure 4(a) and (b), respectively. BAI has the lowest contrast for 10- and 15-μm-diameter channels. RFS achieves the highest contrast enhancement among all four imaging techniques for all channels except 15-μm. CNR separation demonstrates that RFC technique has the better capability to smooth the background than the other techniques. This property is an advantage of the RFC technique over RFS and BAI. Similar results are obtained for the water-filled filled channel in plastic trilaminate film and air/water–channel in aluminum foil film (not shown).

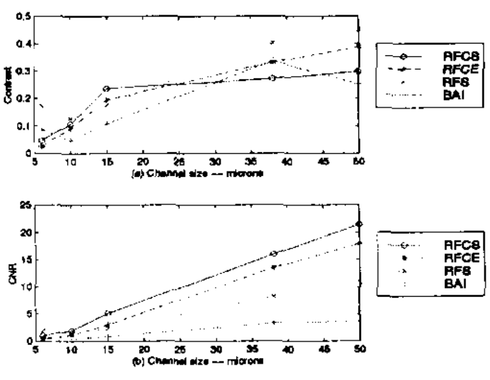

Figure 4. (a) Contrast and (b) CNR, for air-filled channels in plastic trilaminate films.

V. Conclusions

A new imaging technique, the RFC imaging technique is introduced and compared to the BAI and RFS imaging techniques in terms of detection rate, image contrast and contrast-to-noise ratio (CNR). It is experimentally found that RF correlation using a short, specified window (RFCS) has the highest detection rate and greatest CNR enhancement. Also since the correlation is done within a short, specified range, the RFCS technique is more computational efficient than the traditional BAI where the integral of the envelope-detected RF signal is obtained for the entire RF signal range. Future work includes finding a methodology to automatically choose the optimal correlation window for the RFC technique, using image segmentation algorithms to automatically detect channels, and collecting data on a larger number of samples for a complete statistical study.

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