Foreign Object and Internal Disorder Detection in Food Materials Using Noncontact Ultrasound Imaging

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ABSTRACT: A new noncontact air instability compensation ultrasound imaging technique was used for foreign object and defect detection in cheese and poultry. Air instability compensation transducers were used to obtain noncontact ultrasound images of boneless chicken breast with metal and glass fragments and cheese with holes, cracks, and foreign objects. The size of the glass and metal fragments used varied from 2 × 2 to 7 × 7 mm². Results demonstrated that the noncontact ultrasound imaging technique has a good potential for nondestructive and rapid detection of foreign objects and defects in food materials and could provide yet another alternative to conventional x-ray methods.

Keywords: noncontact ultrasound imaging, foreign object, defect, cheese and poultry

Introduction

OF THE MANY SENSING TECHNOLOGIES, ULTRASOUND HAS PROVEN its merit as one of the most promising methods for food safety and quality assessment due to its nondestructive, rapid, and online potential. Ultrasound implies mechanical waves at frequencies above 20 kHz that propagate by vibration of the particles in the medium to penetrate optically opaque materials and provide detailed information of the different physical properties of materials. Ultrasound waves may be reflected and transmitted when they pass from one medium to another. The amount of energy reflected and transmitted through materials depends on their relative acoustic impedances, as defined by the density and velocity of the penetrating wave within and between material interfaces. In addition to the ultrasound energy attenuation, the time-of-flight and velocity could also serve as good indicators of material property or a change in material characteristics since ultrasound velocity is dependent on density and on the elastic property of the medium (Povey and McClements 1988). Thus, in the context of foreign objects such as bone, glass, or metal fragments in cheese and poultry, one would expect a strong reflection and refraction at the interfaces of the host tissue and foreign object interface. Objects such as bone, metals, and glass have different physical properties compared with the medium, and as a result, changes in ultrasound time-of-flight and velocity are expected. To date, the conventional ultrasound measurement uses a coupling medium (oils or gels) between the transducer and test specimen to overcome the high attenuating power due to the large acoustic impedance mismatch between air and material. The coupling media being a chemical agent has the potential to contaminate or interact with the food sample due to absorption, interaction, or its mere presence. Further, the use of a couplant makes the scanning process and online measurement cumbersome.

In the past, x-ray imaging techniques have been widely used in the food industry to detect foreign objects in food materials (MacAndrew and Harris 1991; Tao and others 2001). However, it is an expensive and complex method, which is followed by complicated post–image processing procedures. McFarlane and others (2001) used the Compton scattering approach to detect glass fragments in water. Problems associated with Compton scatter techniques are multiple scatter and low photon fluxes. Detection of a 1-mm fragment was accomplished in 280 s and a 5-mm fragment in 0.018 s. Tao and Ibarra (2000) used plastic molds as a substitute for poultry to detect bone fragments. Tao and others (2001) extended this approach to detect foreign object in deboned poultry. They concluded that the shadow cast by the fillet in the x-ray image was a major source of interference and suggested the need for multiscale processing using a sequence of window sizes.

By using a novel noncontact ultrasound piezoelectric transducer (Bhardwaj 2000) along with improved signal-processing capabilities, the ultrasound system explored has the potential to overcome the limitation of using liquid couplants between the transducer and food samples, thereby eliminating the problem of cross-contamination. Gan and others (2002) investigated the feasibility of noncontact ultrasound imaging of 7- to10-mm metal objects in food containers. However most of the focus of this work was in observing variations in consistency within starch-based liquids.

Since noncontact ultrasound uses air as its medium, the transmitted signal is highly dependent on the conditions of the air, such as temperature, humidity, and airflow. The instability of the air column causes errors in the velocity and thickness measurements in an air-coupled ultrasound system. To compensate for air instability, the transducer performance in varying temperature conditions should be examined in real time for measurement optimization. By using a fixed reference in front of the transducer and collecting the reflected signal with respect to the reference, it is possible to obtain information of the air column between the transducer and the reference from the transmitted signals by examining the velocity and attenuation of the ultrasound waves with respect to the target reference placed in front of the transducer. From the known distance and time-of-flight between the transducer and the reference, the ultrasound velocity through air can be calculated in real time and used in the calculation of ultrasound velocity and thickness of the sample material. In this study, air instability compensation transducers were used for improved noncontact ultrasound velocity and attenuation images of cheese and poultry samples with foreign objects and/or irregularities.

The objectives of this study were (1) to validate the improved performance of the noncontact air instability compensation ultrasound transducers with respect to temperature (26.0 °C to 28.5 °C), (2) to explore the noncontact ultrasound imaging as a tool to detect a variety of foreign objects and internal disorders in cheese and boneless chicken breast.

Materials and Methods

Noncontact air instability compensation ultrasound system

The noncontact ultrasound system uses two 1-MHz piezoelectric noncontact ultrasound transducers (NCT 510, SecondWave System Inc., Boalsburg, Pa., U.S.A.) to measure the thickness, ultrasound velocity, and ultrasound energy attenuation of a sample without any contact. The transducers are connected to an analyzer (NCU1000-2E, SecondWave systems, Boalsburg, Pa., U.S.A.) that can generate synthesized signals and analyze the detected signals simultaneously. The analyzer can measure the time-of-flight up to an accuracy of ±20 ns under ambient air and ±1 ns under constant air property conditions. The transducers operate both as a transmitter and as a receiver, in 4 operational modes: 2 reflection (1 for each of the 2 transducers) and 2 transmission modes (1 used as a transmitter and the other as a receiver and vice-versa). The principle of direct thickness and velocity measurement as given by Bhardwaj (2000) are

$$D_m = V_a \times [t_a - (t_1 + t_2) / 2] \quad (1)$$

$$V_m = D_m / t_m = D_m / [t_c - (t_1 + t_2) / 2] \quad (2)$$

where, D_m is the sample thickness, V_a and V_m are the respective velocities of ultrasound in air and through the sample, t_m is the time-of-flight in the test material, t_a is time-of-flight in air without the sample in between the transducers, t_c is time-of-flight between transducer 1 and transducer 2 with sample, t_1 is the round trip time-of-flight between the transducer 1 and sample, t_2 is the round trip time-of-flight between the sample and transducer 2, t_3 is the round trip time-of-flight between transducer 1 and reference, and t_4 is the round trip time-of-flight between transducer 2 and reference (Figure 1).

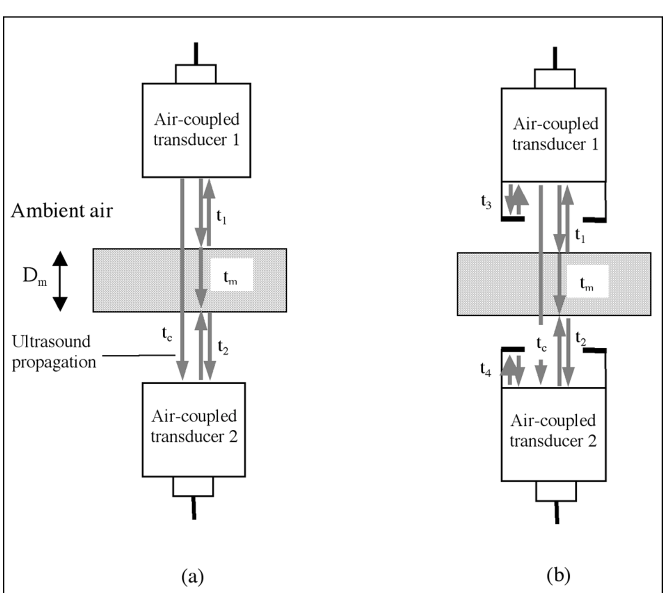

Figure 1—A schematic of the noncontact ultrasound measurement with (a) normal noncontact ultrasound transducers and with (b) noncontact air instability compensation transducers

From the above equations, every value is updated in real time except the air velocity (V_a) and time-of-flight in the air column (t_a), which are decided from the initial calibration and fixed during the measurements. Since the air velocity and time-of-flight in the air column are dependent on the air temperature, humidity, and/or airflow rate, the value is prone to vary when the air property values are not stable during measurements. Hence, the air velocity and time-of-flight in the air column should be updated in real time during monitoring for improved thickness and velocity measurements and used as a calibration standard.

A ring shape reference is placed in front of each air-coupled transducer to monitor the air property changes of the air column between a transducer and a reference continuously. The reference is designed to limit the reflected energy to as low as possible so that most of the energy is directed to the sample (Cho and Irudayaraj 2002). After the initial calibration, the time-of-flights in the air column are monitored continuously and used to compensate for the initial calibration error caused by air property changes.

In addition to thickness and velocity measurement, the ultrasound energy attenuation through the material can be estimated using the integrated response (IR). The IR is a measurement of the area underneath the most significant peak above –6 dB of the cross-correlated transmitted signal in dB units (Bhadwaj 2000). The IR provides information of the decrease in energy of the transmitted ultrasound signal through the sample in the time domain. The relative attenuation is calculated by subtracting the integrated response of the transmitted signal through the sample from that of the air column divided by sample thickness (Cho and others 2001). The relative attenuation contains information of the attenuation by reflection on the upper and lower surface of the material as well as the attenuation by absorption and scattering in the material throughout the thickness. To minimize the error caused by diffraction on the sample surface, the sample surface should be kept parallel to the transducer.

Using the characteristic of through-transmission the attenuation coefficient can be calculated from the signal. Figure 2 shows a typical through-transmission signal of a 25-mm-thick polystyrene block with several peaks. The first peak is the transmitted signal through air and sample material, and the second peak is the transmitted signal with a material internal reflection. The other periodic peaks are due to multiple reflections by the sample material and transmitted signals. Usually the first and second peaks can be observed in food materials. However, the second peak is hardly observed in nonhomogeneous food or food materials such as vege-

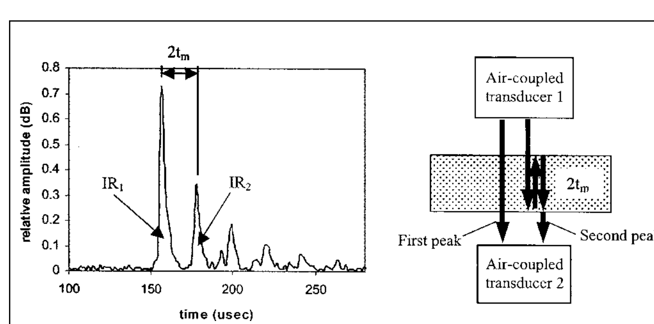

Figure 2—Signal transmitted through a 25-mm-thick polystyrene block

tables that have a high attenuation rate. The attenuation coefficient is obtained by the difference between the integrated response of the first and the second peak divided by the sample thickness.

Image scanning system

The noncontact ultrasound system consists of an X-Y positioning system to obtain ultrasound image of samples (Figure 3). All scanning and data acquisition were controlled by a Pentium II computer via a parallel interface and a real-time operating system (QNIX). Parameters measured are velocity, relative attenuation, and attenuation coefficient through the sample. Usually the scan area is set at 20×20 mm, at spatial intervals of 1 mm by default. The scanned data were transferred to a PC and visualized using the Matlab software (Version 6.0, The Mathworks Inc., Natick, Mass., U.S.A.).

Calibration of ultrasound measurement

The noncontact ultrasound system was calibrated before measurement with a 25-mm polystyrene block and a Dow Corning (DC) 710 silicon fluid cylinder contained in a plastic film (Saran wrap, Johnson & Son, Inc.; Racine, Wis., U.S.A.). After aligning the transducers parallel to each other and verifying the shape of the received signal, the polystyrene block was inserted between the 2 transducers. The calculated thickness was compared with the actual thickness, and the calculated value was adjusted by changing the system parameters until the error was within 0.1%. After the thickness calibration, a 30-mm-thick DC 710 silicon fluid cylinder was placed between the 2 transducers to verify velocity measurement. Since the DC 710 silicon fluid provides a very stable condition to obtain ultrasound information, it is widely used for ultrasound system calibration (Haney and O'Brien 1986; Zeqiri 1989).

Sample preparations

Two percent milk sharp, sharp, extra sharp, and Vermont sharp white Cheddar cheese (Kraft foods Inc. Glenview, Ill., U.S.A.) were purchased from the local grocery store. Cheese blocks were equilibrated at room temperature for 12 h, and $45 \times 45 \times 25$-mm samples were cut from each block of cheese (0.28 kg) using a specially designed wire cutter to provide an even surface for minimizing the diffraction effects. In addition to cheese samples, boneless and skinless poultry breasts were purchased from a local grocery store (Weis, State College, Pa., U.S.A.), and $50 \times 50 \times 15$-mm pieces were sectioned off and equilibrated at room temperature for 12 h. Each sample was wrapped in a plastic film to avoid dehydration until measurement. Usually, poultry breasts are of uneven thickness and shape, which causes ultrasound diffraction at the sample surface, making measurement difficult. To avoid unreasonable measurements, thin polystyrene panels (0.8 mm thick) were placed on both sample surfaces to maintain parallel thickness.

To investigate foreign objects in food materials, 3 types of foreign objects such as metal rod, metal fragments, and glass fragments were prepared. Several dimensions of each object were used to observe the sensitivity of the noncontact ultrasound image for a variety of foreign object detection experiments.

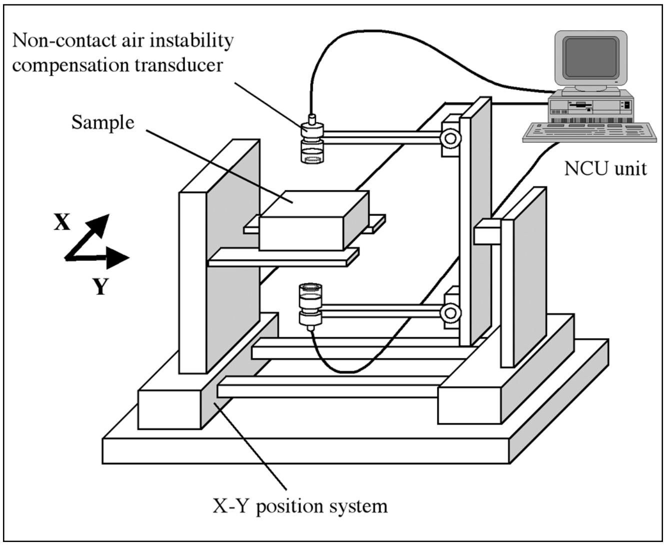

Figure 3—Schematic of the noncontact ultrasound imaging system

Results and Discussion

Performance of noncontact air instability compensation ultrasound measurements

To investigate the performance of a noncontact air instability compensation ultrasound transducer for the thickness and ultra-

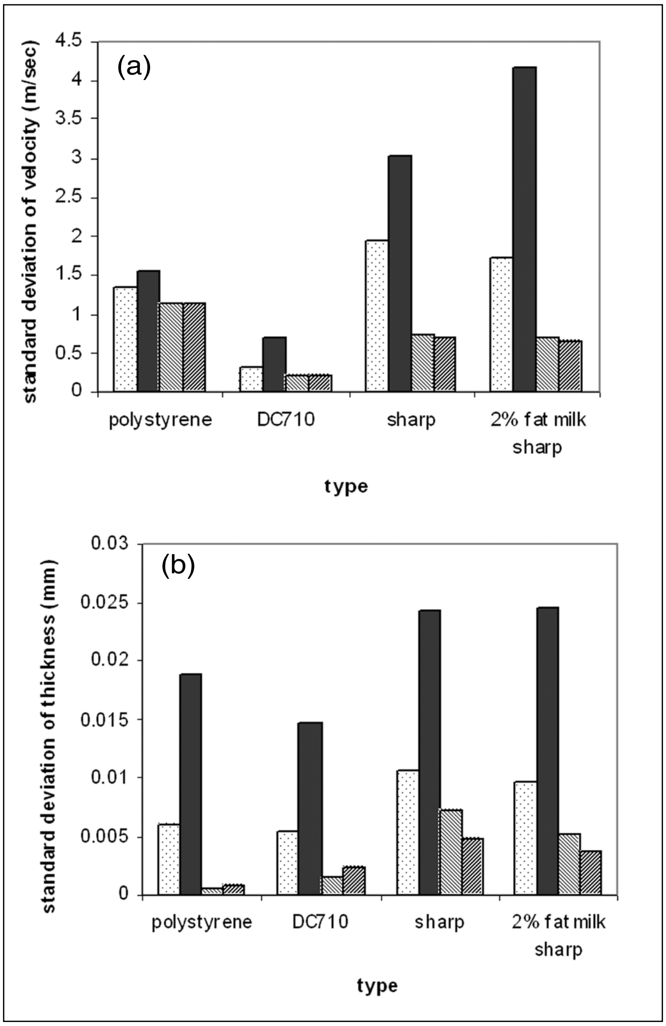

Figure 4—Standard deviation values of velocity (a) and thickness (b) measurements for 150 s from polystyrene, Dow corning 710, sharp cheddar cheese, and 2% fat milk sharp cheddar cheese in temperature-stable (□) and unstable (■) environments using normal NCU transducers, and in temperature-stable (light grey) and unstable (dark grey) environments using noncontact air instability compensation transducers.

sound velocity measurements, the thickness and velocity values of the samples with compensated transducers were recorded continuously at varying (26.0 °C to 28.5 °C) air temperature conditions and compared with the values from the experiment with normal noncontact ultrasound transducers. The system was calibrated at 26.0 °C, and then the air temperature was increased up to 28.5 °C using six 60-W bulbs placed in a plastic case enclosing the ultrasound system. The air temperature was monitored (accurate to ±0.3 °C) using a T type thermocouple (Nylon Duplex 250F, Thermo Electric, Saddle Brook, N.J., U.S.A.) with a data acquisition switch unit (HP 34970A, Hewlett Packard; Englewood, Colo., U.S.A.) transferred to a PC through a parallel port while ultrasound parameter values were collected from the NCU1000-2E to a PC through a RS-232 cable using a serial port data transfer. The temperature and ultrasound parameters were collected simultaneously using Labview software (Version 6.0, National Instruments, Austin, Tex., U.S.A.).

Standard deviations of velocity and thickness measurements from compensated and uncompensated noncontact ultrasound measurements were compared at constant and varying temperature conditions in Figure 4. The measurements were repeated 3 times for each specimen, such as Polystyrene (25 mm thick), DC 710 (approximately 30 mm thick), and 2 types of sharp cheddar cheese (approximately 25 mm thick) and the values were averaged. When the normal noncontact transducers were used in varying temperature conditions, the errors of the standard deviations were 15% to 145% for velocity measurements and 125% to 210% for thickness measurements. However, the errors of the standard deviations of velocity and thickness from the temperature compensating transducers were only 0% to 8% and 25% to 60%, respectively. These results indicate that the effects of varying air property on velocity and thickness measurement were reduced, and improved stability of the measurements could be obtained with the compensated transducers. The results of the polystyrene, DC 710, and cheddar cheese are not identical possibly due to the different acoustic properties of the materials.

Noncontact ultrasound images for foreign object detection

Noncontact ultrasound images were scanned to investigate foreign objects in cheese and poultry. Figure 5 and 6 show the respective raw noncontact ultrasound (NCU) images and transformed images of relative response and velocity values of a glass fragment approximately 7 × 7 mm^2 in sharp cheddar cheese and 4-mm-dia steel rod inserted into poultry breast. The original images were

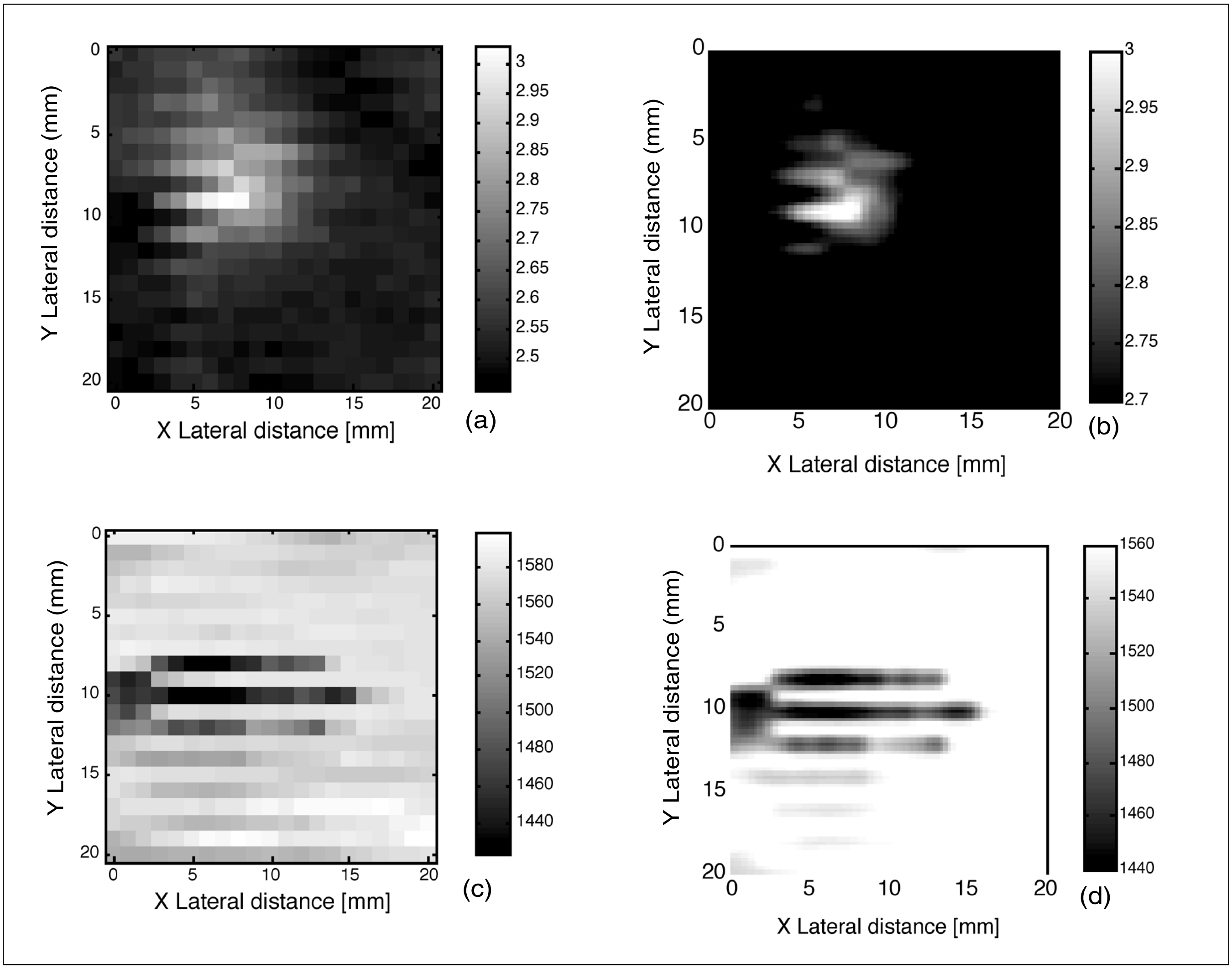

Figure 5—Comparison of raw (a) and modified (b) image of relative attenuation and raw (c) and modified (d) image of velocity of a glass fragment placed in a sharp cheddar cheese

smoothed using interpolation in which the value of an interpolated point was a combination of the values of the 16 closest points, and the color ranges were optimized. As shown in the transformed images, the round shape of the glass fragment and linear shape of the steel rod are clearly observed in their approximate sizes. The differences between actual and scanned shape are due to diffraction and refraction effects as well as the 12.5-mm active diameter of ultrasound transducer, which provides overlapped images (Gan and others 2002). In general, the relative response provides better images than those of velocity. This is to be expected since the ultrasound energy attenuation is more sensitive to the difference in product characteristics than velocity. In addition, the induced pressure produced when the foreign objects were inserted into the sample may cause other measurement error.

Ultrasound attenuation includes ultrasound absorption and scattering. Absorption involves the conversion of the propagating energy permanently into heat energy. Usually, internal friction caused by viscosity is a main reason for the absorption of ultrasound by solids (Nielsen 1996). When an ultrasound wave travels through a nonuniform medium, such as a foreign object embed-

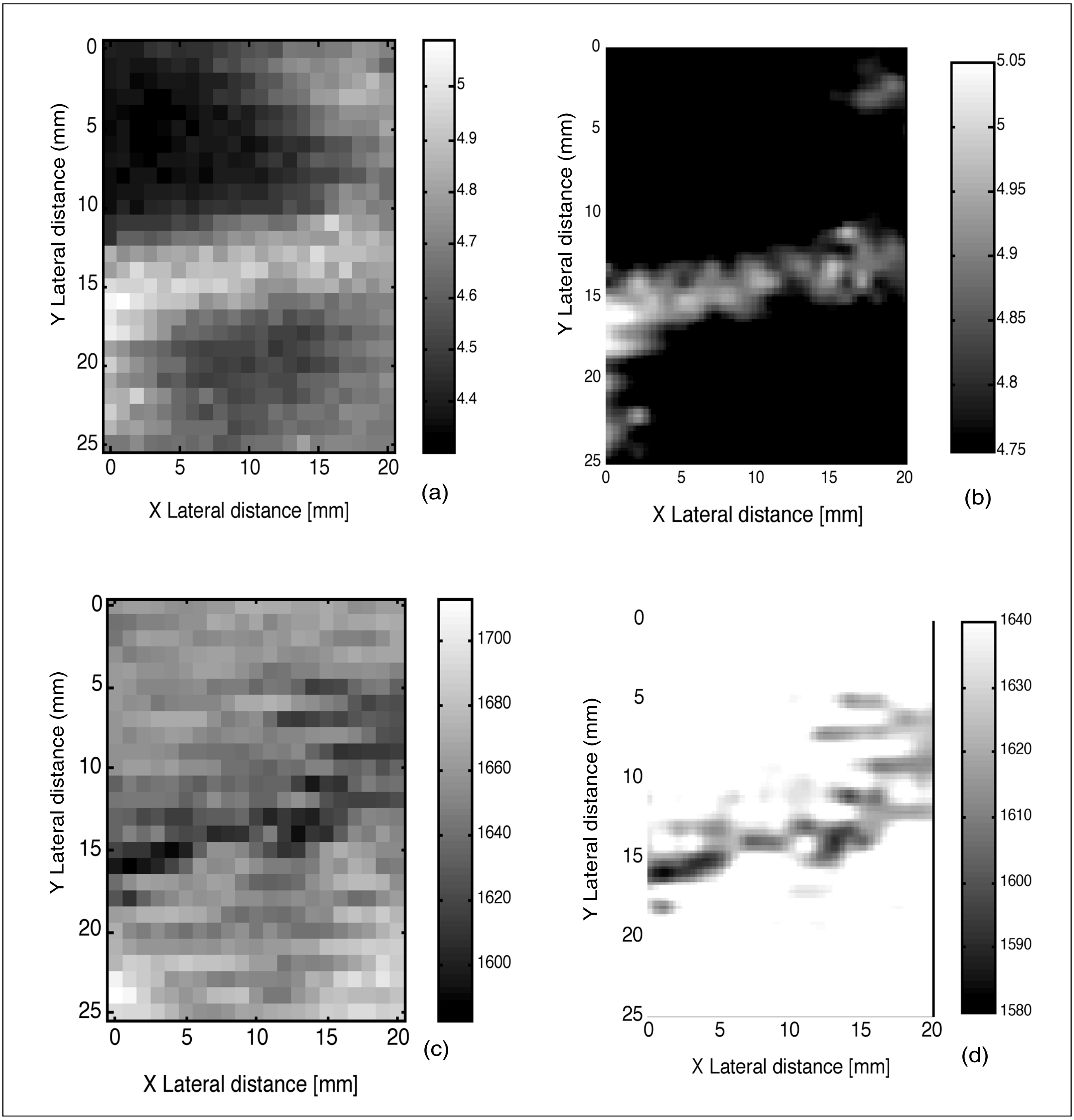

Figure 6—Comparison of raw (a) and modified (b) image of relative attenuation and raw (c) and modified (d) image of velocity of a 4-mm-dia steel rod inserted into a poultry breast

Food Engineering and Physical Properties ded material, there is scattering, in which part of the wave changes its initial direction and propagates separately from the original incident wave, distorting and interfering with the initial wave. The discontinuity within a medium plays a role in scattering the signal; hence in nonhomogeneous material, scattering affects the attenuation more than the absorption.

Several foreign objects and artificial defects were introduced at the surface or embedded inside cheese blocks. An NCU image of

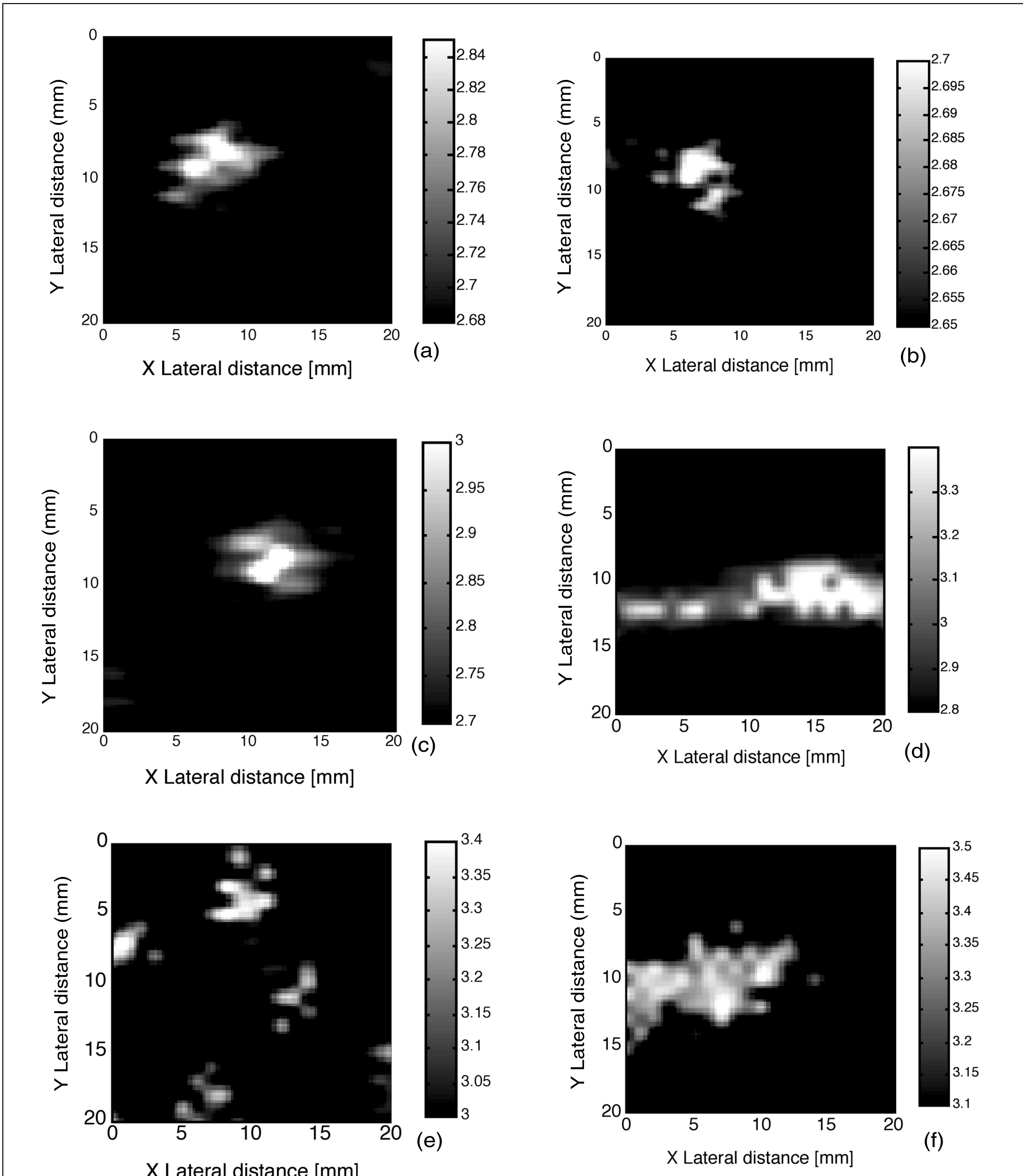

Figure 7—Modified NCU relative attenuation images of a metal fragment (5 × 3 mm²) (a) and a glass fragment (3 × 3 mm²) (b) in a sharp cheddar cheese, vertical hole (4-mm dia) at the bottom of a 2% fat milk sharp cheddar cheese (c), horizontal hole (4-mm dia) in the middle of a 2% fat milk sharp cheddar cheese (d), sporadic holes in a Vermont sharp white cheddar cheese (e), and a crack in extra sharp cheddar cheese (f).

relative attenuation could clearly detect metal or glass fragments up to a minimum of 3 × 3 mm^2 on the food surface and cylindrical objects as small as 1.5 mm in diameter in food material. Figure 7 shows the noncontact relative attenuation images of metal fragment (5 × 3 mm^2), glass fragment (3 × 3 mm^2), and artificial holes (4-mm-dia vertical and horizontal holes). The objects and holes were detected with the correct location and reasonable dimensions. In addition to artificial objects and holes, some unidentified blocks

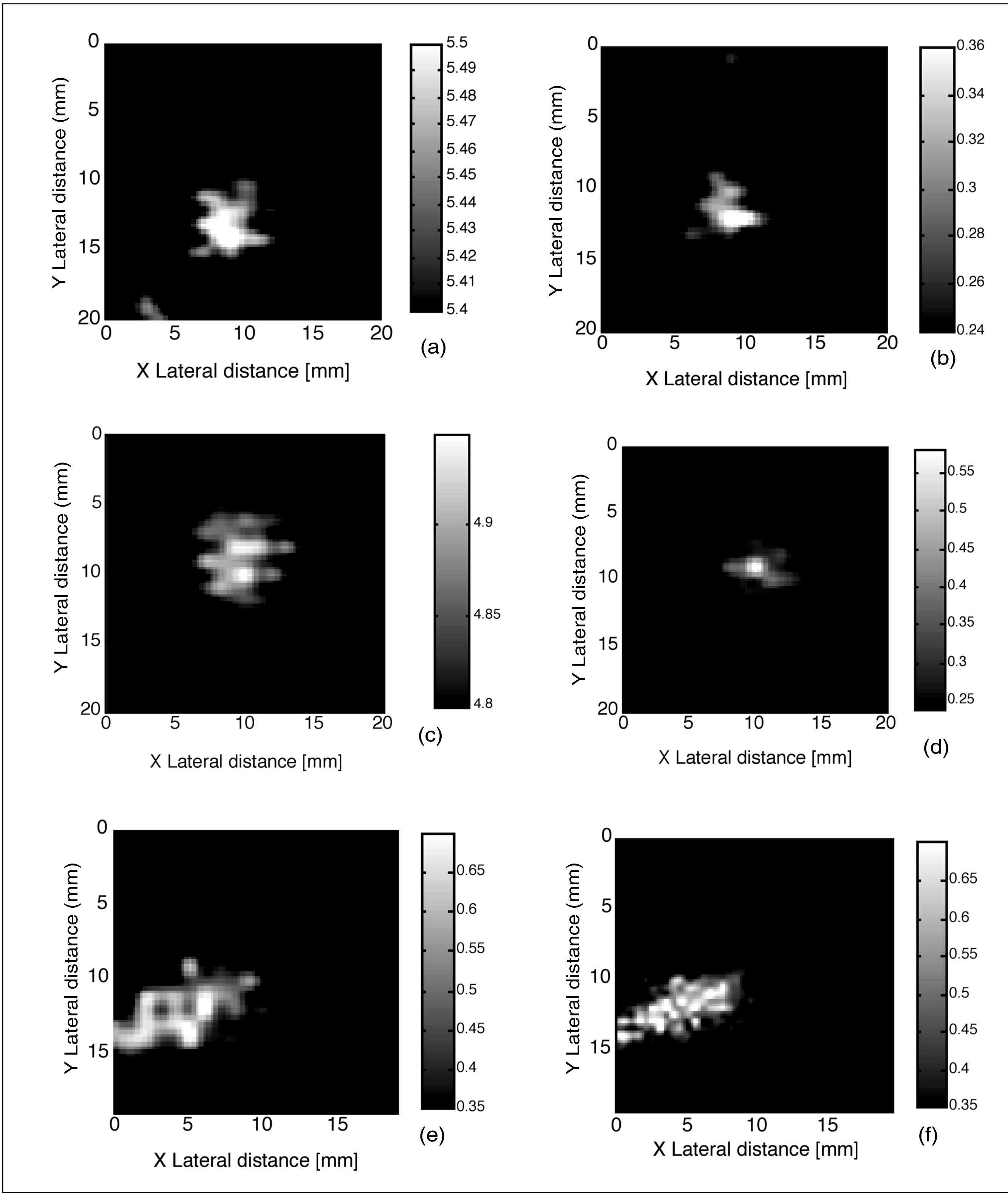

Figure 8—Modified NCU images of relative attenuation (a) and attenuation coefficient (b) of a metal fragment (5 × 3 mm^2), relative attenuation (c) and attenuation coefficient (d) of a glass fragment (3 × 3 mm^2), attenuation coefficient due to a steel rod (4-mm dia) embedded in a poultry breast with 1-mm (e) and 0.5-mm scanning step size.

of Vermont sharp and extra sharp cheddar cheese were scanned to investigate their non-uniform characteristics since air bubble and cracks were frequently observed in the cheese samples examined. The sporadic holes and a relatively long crack embedded in the cheese blocks were detected with NCU images as demonstrated in Figure 7e and 7f.

NCU images of relative attenuation and attenuation coefficient of metal and glass fragments in poultry are shown in Figures 8a through 8d. Since the second peak of through-transmission NCU signal is clearly obtained in boneless poultry measurements, which is hardly observed in cheese measurements, the images of attenuation coefficient could be constructed. The images of attenuation coefficient and relative attenuation provide a clear indication of metal and glass fragments in poultry. When the steel rod is placed in the poultry, the images of attenuation coefficient show the position and dimension of the incursion much more clearly than those of relative attenuation. This is to be expected because of the large difference in attenuated energy between the second and the first peak. The second peak is from a signal that passes through the foreign incursion 3 times due to an internal reflection while the first peak is from the signal that passes through it only once. The large scatterings occur when the second peak signal is propagated through the incursion repeatedly whereby distinguishing the position and dimension of the foreign incursion clearly.

Experiments on the step size of scanning on image quality indicated that when the step size was reduced to 0.5 mm instead of 1 mm, more identical images were observed as shown in Figure 8e and 8f. The scanning time takes 90 s with a 1-mm step size for a 20×20 mm^2 image. However, the period is increased to 6 min, which is 4 times when a 0.5-mm step size was used. Hence, the scanning region and step size need to be optimized for each application.

Conclusions

The noncontact air instability compensation ultrasound transducers improved the velocity and thickness measurements of the calibration standard in a varying temperature (26.0 °C to 28.5 °C) environment. Even though the advantages of the air instability compensation transducer did not affect the images of velocity due to low-quality images, accurate images of relative attenuation and attenuation coefficient could be obtained with the stable thickness calculation. The minimum 3×3 mm^2 foreign fragments in cheese and poultry and 1.5-mm-dia cylindrical objects in the food materials could be clearly detected, even though the images were distorted by diffraction and refraction effects. However, it was difficult to recognize the differences between fragments and internal disorders in foods. To discriminate the foreign objects from food materials, quantitative analysis needs to be performed by using the absolute values of ultrasound parameters of foods and foreign objects. In addition, a better scan system and a higher frequency ultrasound transducer integrated with advanced signal processing technique need to be developed to detect smaller foreign fragments at higher scanning speeds.

The results of NCU images demonstrate its potential as a nondestructive, rapid, and economic tool to detect the presence of foreign objects and defects inside food materials. Further study is needed on NCU imaging of food materials of uneven or irregular shapes for calibration and use in online detection under actual production setting. To the authors' knowledge, this is the first application of noncontact air instability compensation ultrasound imaging of foreign object detection in solid foods.

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MS 20020501 Submitted 8/30/02, Revised 12/15/02, Accepted 1/9/03, Received 1/10/03

The authors express their sincere appreciation to Dr. Mahesh Bhardwaj and Gary Stead of SecondWave Systems for providing generous access to the image scanning equipment and technical support.

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