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Nondestructive Measurement of Cheese Texture using Noncontact Air-instability Compensation Ultrasonic Sensors

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Abstract

Purpose: Cheese texture is an important sensory attribute mainly considered for consumers' acceptance. The feasibility of nondestructive measurements of cheese texture was explored using non-contact ultrasonic sensors. **Methods:** A novel non-contact air instability compensation ultrasonic technique was used for five varieties of hard cheeses to measure ultrasonic parameters, such as velocity and attenuation coefficient. Five texture properties, such as fracturability, hardness, springiness, cohesiveness, and chewiness were assessed by a texture profile analysis (TPA) and correlated with the ultrasonic parameters. **Results:** Texture properties of five varieties of hard cheese were estimated using ultrasonic parameters with regression analysis models. The most effective model predicted the fracturability, hardness, springiness, and chewiness, with the determination coefficients of 0.946 (RMSE = 21.82 N), 0.944 (RMSE = 63.46 N), 0.797 (RMSE = 0.06 ratio), and 0.833 (RMSE = 17.49 N), respectively. **Conclusions:** This study demonstrated that the non-contact air instability compensation ultrasonic sensing technique can be an effective tool for rapid and non-destructive determination of cheese texture.

Keywords: Cheese texture, Food quality, Non-contact ultrasonic, Nondestructive measurement, Sensor

Introduction

Texture is one of the most significant qualitative attributes of cheese since it determines the identity and quality of a specific variety of cheese (Fox et al., 2000). Cheese texture has been considered as a sensory characteristic affected by mechanical and fracture properties within the mouth during chewing (Lawrence et al., 1993). Hence, texture of different cheese varieties is governed by the characteristics of composition, microstructure, and the physico-chemical state of the specimens.

Although instrumental analyses of texture properties of cheese are important for objective quality measurement, most methods are destructive either partially or entirely. In addition, these methods are time consuming and labor intensive manner. Unfortunately, there is no standard method to meet for objective, non-destructive, and rapid determination of the cheese quality even though the demand of nondestructive and rapid quality control for cheese has increased.

Ultrasonic is one of the promising sensing technologies for food quality measurement due to its nondestructive, rapid, and readily automated potential. In addition, owing to the excellent propagation ability through the opaque material, ultrasonic signal can provide high quality information of the inside characteristics of a specimen both at the micro and macro level that most optical sensors cannot afford.

Recently, non-contact ultrasonic sensors (NCU) are available as a novel alternative to conventional contact ultrasonic sensors, especially for food quality measurements, since it eliminates not only the contact-caused contamination but also the contact procedures which make the scanning process and on-line measurement cumbersome. Cho et al. (2001) utilized a non-contact ultrasonic technique to measure the mechanical properties of cheddar cheese, demonstrating the feasibility of the non-contact ultrasonic

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procedure for rapid assessment of mechanical properties of cheese. However, the variation of sample temperature and its effect on air temperature instability introduces an error in measurement.

Since air is the key medium in non-contact ultrasonic measurement, it is highly dependent on the air conditions, such as temperature, humidity, and air flow. For this reason, instability of the air column between ultrasonic sensors is a main source of errors in non-contact ultrasonic measurements. Hence, it is necessary to develop an air instability compensation technique. Cho and Irudayaraj (2003a) studied the design of a non-contact air instability compensation ultrasonic sensor using a computer simulation model and demonstrated its improved performance over that of a normal non-contact ultrasonic sensor. They also applied the air instability compensation ultrasonic sensors for determination of mechanical properties of five different types of cheeses (Cho and Irudayaraj, 2003b). This study showed the feasibility of the air instability compensation non-contact ultrasonic sensors for the prediction of the mechanical properties, such as Young's modulus, hardness and toughness. It was assumed that the non-contact ultrasonic sensors could be applied to measurements of the expanded texture parameters analyzed by a texture profile analysis (TPA) designed to simulate the compression of cheese between the molars during chewing.

The objectives of this study were (1) to investigate the feasibility of a non-contact air instability compensation ultrasonic technique for measurement of texture properties of hard cheese varieties, and (2) to develop calibration models using statistical analysis for improved prediction of texture properties of cheeses.

Materials and Methods

Sample preparation

Five varieties of hard cheese (Sharp Cheddar, Reduced fat sharp Cheddar, Asiago, Romano, and Parmesan) were purchased from the local grocery store and equilibrated to room temperature (25±1℃) for 12 h before measurement. A cube 25×25×25 mm size was prepared from each block of cheese using a wire cutter and then used for ultrasonic and texture measurement. Total 105 samples from twenty one samples of each type of cheese were prepared for the measurements.

Noncontact ultrasonic measurements

The ultrasonic velocity and attenuation coefficient of transmitted signal through the prepared cheese sample were measured. Figure 1 showed the scheme of the noncontact ultrasonic sensor system with air instability compensation. The system consists of two 1 MHz piezoelectric noncontact ultrasonic sensors (NCT 510, Second Wave System Inc., Boalsburg, PA) with a ring shape reference placed in front of the sensors' surface, and an analyzer (NCU1000-2E, Second Wave systems, Boalsburg, PA) which can generate and capture the synthesized signals simultaneously. Each transducer operates both as transmitter and as receiver, and hence provides four operational modes with two reflection modes (one for each of the two transducers) and two transmission modes (one used as transmitter and the other as receiver and vice-versa). Using the four operational modes, real time calculation was possible regarding the sample thickness, velocity of sample, and attenuation coefficient. Detailed technical information is provided by Cho and Irudayaraj (2003a).

Five different sites on a sample were measured and the values were averaged. Each measurement is an average of 20 readings. After each measurement of ultrasonic parameters for the sample, the texture properties were evaluated. The velocity of the transmitted signal through

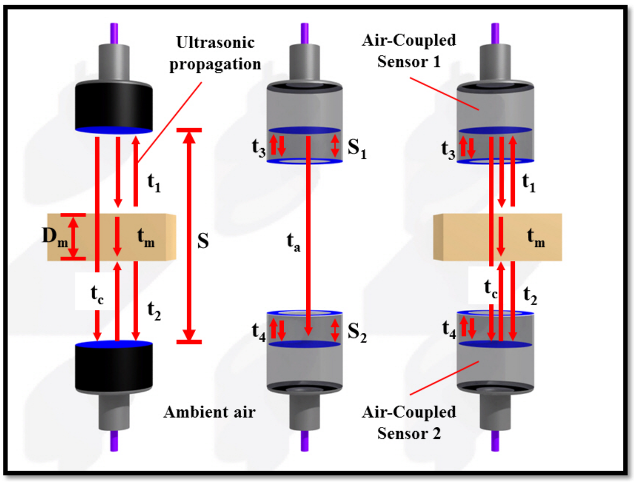


Figure 1. A schematic non-contact air instability compensation ultrasonic sensor system, where, t_m is the time-of-flight in the test material, ta is time-of-flight between sensor 1 and sensor 2 in air, t_c is time-of-flight between sensor 1 and sensor 2 with sample, t_1 is the round trip time-of-flight between sensor 1 and sample, t_2 is the round trip time-of-flight between the sample and sensor 2, t_3 is the round trip time-of-flight between the sensor 1 and reference, and t_4 is the round trip time-of-flight between sensor 2 and reference.

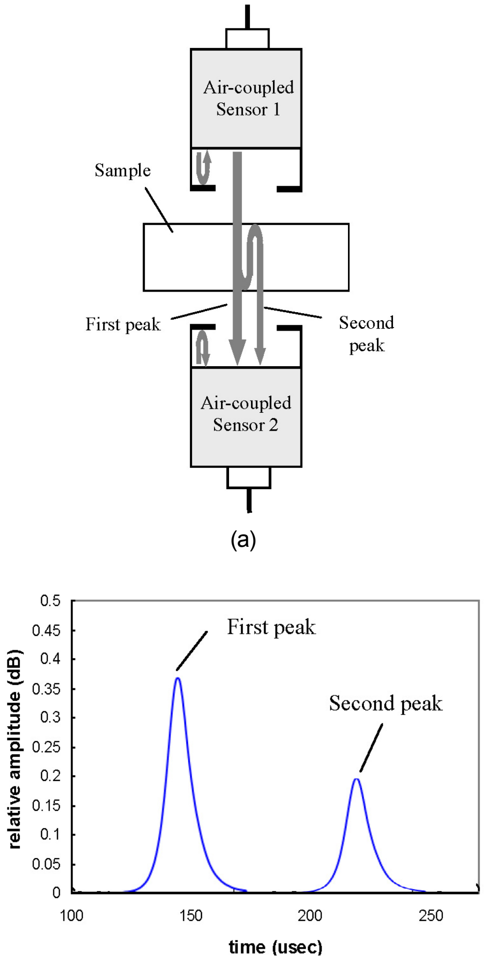
the sample could be calculated as follows,

$$D_m = S - \left[\left(S_1 \times \frac{t_1}{t_3}\right) + \left(S_2 \times \frac{t_2}{t_4}\right)\right] \tag{1}$$

$$V_m = \frac{D_m}{\left[\frac{t_c - (t_1 + t_2)}{2}\right]} \tag{2}$$

where, D_m is the thickness of the sample, and V_m is the transmitted ultrasonic velocity through the sample.

Along with the ultrasonic velocity measurement, the ultrasonic energy attenuation was measured. The integrated response (IR), a measurement of the area underneath the peak above -6 dB of the transmitted signal in dB units, provides information of the energy of the transmitted ultrasonic signal through the sample in the time domain. Using the characteristic of through-transmission, the attenuation coefficient can be calculated from the signal. Figure 2 shows a typical through-transmission measurement and its signal from a sample. The first peak is the transmitted signal through air and sample material and the second peak represents the transmitted signal with a sample internal reflection. The attenuation coefficient is obtained by the difference between the integrated response of the first and the second peak divided by the sample thickness. Five different sites on a sample were measured and the values were averaged. Each measurement is an average of 20 readings.



(a)

(b)

Figure 2. Scheme of the through-transmission measurement (a) and a typical non-contact ultrasonic signal transmitted through a sample (b).

Texture property measurement

Five texture parameters of cheese, such as fracturability, hardness, springiness, cohesiveness, and chewiness were measured using Instron testing machine (Model 4444, Instron, Canton, MA). The texture profile was obtained using Labview software (Version 6.0, National Instruments, Austin, TX) and saved as a text file. The obtained texture profiles were analyzed using Matlab software (Version 6.0, The Mathworks Inc., Natick, MA) as shown in Figure 3. Speed of the Instron crosshead (100 mm in diameter) was kept at 50 mm/min, and the sample was deformed to 80% of its original height (Rao, 1992). All tests were done in room temperature (25±1℃).

Isotropy test

It is known that ultrasonic velocity is related to the square root of Young's modulus divided by density of the homogeneous and isotropic materials. Testing isotropy of the materials helps to understand the relationship

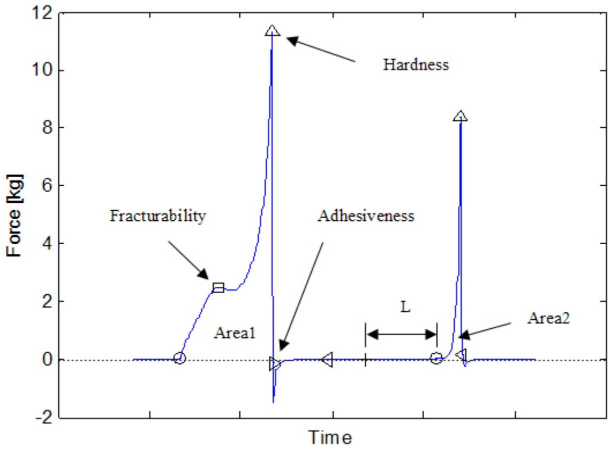


Figure 3. A typical texture profile curve of cheese.

between ultrasonic velocity and physical parameters of the materials. The effects of sample orientation on texture properties were investigated by applying texture analysis to the cheese blocks on three different orientations (i.e. X, Y, and Z). Seven samples of each orientation were prepared for a total 21 samples of each type. Using Tukey multiple comparison procedure (Neter et al., 1996), the texture properties of each orientation were compared with a significant level of 0.05. Minitab statistical software (Version 12, Minitab Inc., State College, PA.) was used for statistical analysis.

Statistical analysis

The ultrasonic parameters and the properties of cheese were correlated to develop the regression models. Comparisons were considered significant at the p-value < 0.05. To statistically compare the developed models, determination coefficient (R^2) and the root mean squared error of the estimation (RMSE) between the actual and predicted values were calculated as defined by

$$\mathrm{RMSE} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(Y_i - \hat{Y}_i)^2} \qquad (3)$$

where Y_i and $\hat{Y}_i$ are actual and predicted values, respectively and N is the number of samples.

Results and Discussion

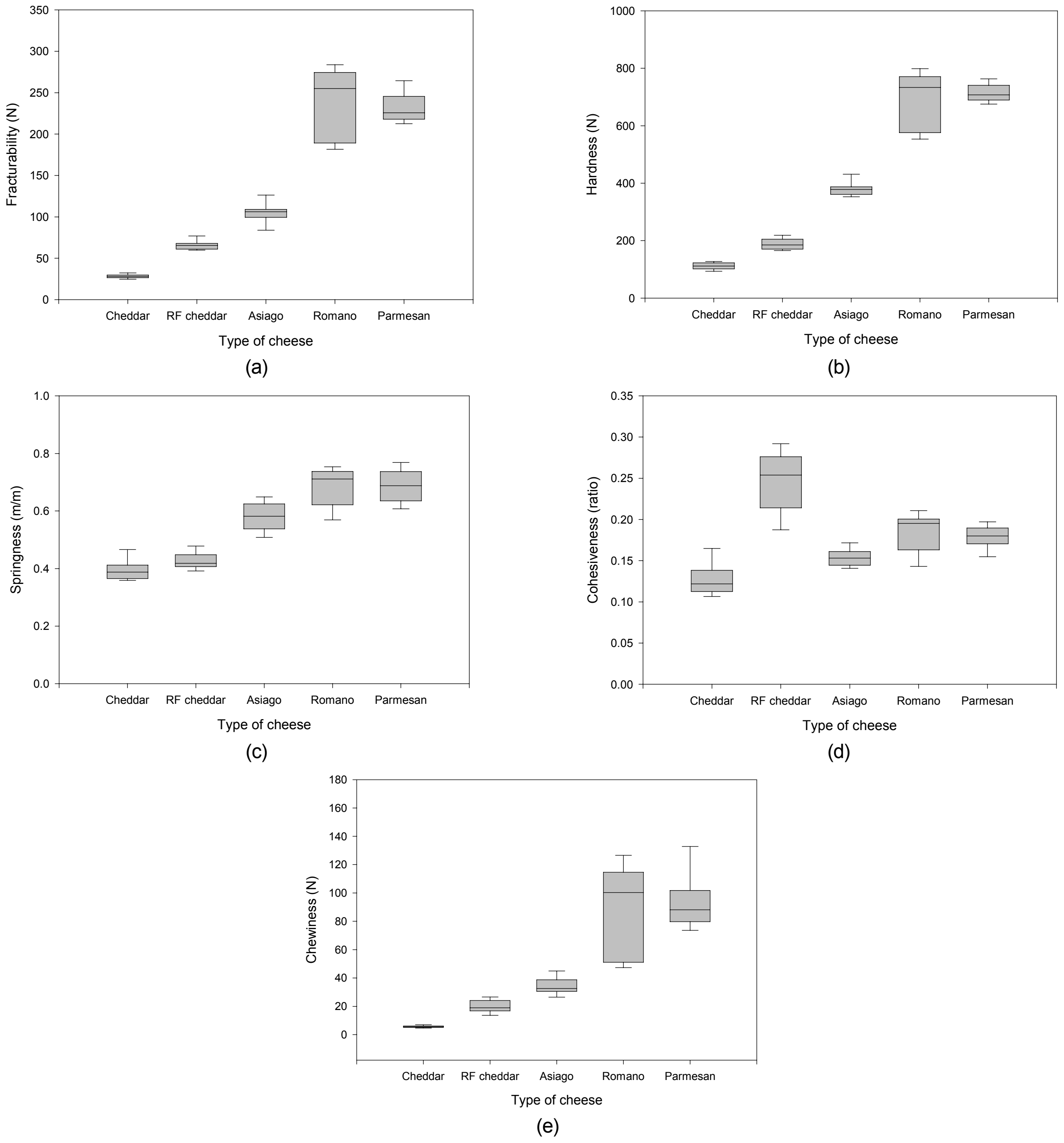
The isotropy of cheese texture was investigated through comparing the texture values of three different orientations. The results of Tukey multiple comparisons are listed in Table 1, which demonstrate that the effects of

Table 1. Tests of Tukey pairwise differences for the texture parameters

Parameter		Pairwise tests			Critical value (α = 0.05)	Isotropic
		X-Y	Y-Z	Z-X		
Reduced fat sharp cheddar	Fractuability	2.04	2.11	0.06	3.63	YES
	Hardness	0.67	0.59	1.23		
	Springiness	0.04	0.06	0.02		
	Cohesiveness	0.33	0.34	0.02		
	Chewiness	0.14	0.96	1.10		
Sharp cheddar	Fractuability	1.09	1.93	0.83	3.61	YES
	Hardness	1.83	0.39	1.45		
	Springiness	2.37	2.10	0.27		
	Cohesiveness	0.45	1.77	2.23		
	Chewiness	0.41	0.76	1.16		
Asiago	Fractuability	1.79	0.57	1.26	3.63	YES
	Hardness	1.03	0.29	0.77		
	Springiness	1.78	0.97	0.85		
	Cohesiveness	0.83	1.69	2.63		
	Chewiness	1.69	0.12	1.89		
Romano	Fractuability	1.69	3.42	1.74	3.61	YES
	Hardness	1.53	3.54	2.21		
	Springiness	2.01	3.52	3.40		
	Cohesiveness	0.23	3.48	3.41		
	Chewiness	1.52	3.38	2.86		
Parmesan	Fractuability	0.64	0.35	0.28	3.61	YES
	Hardness	1.62	1.82	0.21		
	Springiness	0.00	1.54	1.41		
	Cohesiveness	0.01	0.65	0.64		
	Chewiness	1.85	0.59	1.25		

orientation were not significant for texture parameters. Hence, the five varieties of cheese used in this study can be assumed to be isotropic with respect to texture.

The results of each texture parameter are presented in Figure 3. Fracturability, hardness, and chewiness have similar trends irrespective of the type of cheese. In general, the cheeses which have higher protein, lower moisture, and reduced fat content, such as Romano and Parmesan displayed high values for fracturability, hardness, and chewiness. The high protein ratio increases the amount of the structural matrix per unit volume in cheese and leads to higher firmness and elasticity (Emmons et al., 1980) which may explain the texture behavior of the extra hard cheeses. The values of above 4 texture properties increase as fat content decrease, consistent with the previous studies (Irudayaraj et al., 1999; Bryant et al., 1995). However, the reduced fat cheddar did not show greater values of the texture parameters than those of



(a) (b) (c) (d) (e)

Figure 4. Distribution of texture property of five different types of cheese. (a) fracturability, (b) hardness, (c) springiness, (d) cohesiveness, and (e) chewiness.

other cheeses although its fat content is the lowest of the cheeses. A possible reason might be its high moisture content which increases plasticity in the protein matrix, and thus decrease elasticity and resistance to deform under compression (Fox et al., 2000). Of the texture properties, the distribution of cohesiveness, which depicts the strength of internal bonds, was quite different to that of other parameters. The increase in cohesiveness was strongly dependent on the decrease in fat content. As fat is reduced, fat globules available to break up the protein matrix decrease, hence cheese becomes rubbery and not easy to rupture (Bryant et al., 1995), which assumed to strengthen the internal bonds of cheese.

Most texture property values tended to increase with an increase in ultrasonic parameters except cohesiveness in which significant relations were not observed with ultrasonic parameters ($R^2 < 0.2$). The texture parameters, such as fracturability, hardness, springiness, and chewiness were well estimated by the ultrasonic velocity modeled by a quadratic regression. They were also fairly correlated with ultrasonic attenuation coefficient using a nonlinear power regression model. The regression models are presented in table 2 and 3.

Ultrasonic velocity is assumed to be related to the square root of bulk modulus over density of the solid material (Povey, 2001). Since the density differences of the cheese varieties are not significant, the ultrasonic velocity is determined by the bulk modulus which might be strongly interdependent on texture properties. Hence, the texture properties were well explained by a quadratic regression model with determination coefficients of 0.946 (RMSE = 21.82 N), 0.944 (RMSE = 63.46 N), 0.797 (RMSE = 0.06 ratio), and 0.833 (RMSE = 17.49 N) for fracturability, hardness, springiness, and chewiness, respectively.

The correlation between ultrasonic attenuation coefficient and texture parameters showed relatively high variability ($R^2 < 0.7$). Even though the attenuation coefficient is assumed to be related with physical properties of a material, such as viscosity, density, and ultrasonic velocity, accurate measurement of the attenuation coefficient using non-contact ultrasonic technique is difficult task due to its sensitiveness to uneven sample surface, tiny defects, porosities, and uneven component distribution in sample materials. Special care is required in sample preparation to minimize the errors; however, possible errors could not be completely eliminated.

Both ultrasonic velocity and attenuation coefficient were simultaneously included to estimate texture properties using multivariate linear regression analysis. The regression model explained the sample variation with determination coefficients of 0.949 (RMSE = 21.12 N), 0.952 (RMSE = 58.90 N), 0.827 (RMSE = 0.058 ratio), and 0.838 (RMSE = 17.22 N) for fracturability, hardness, springiness, and chewiness, respectively. Detail results of multi-

Table 2. Regression model to predict textual properties with NCU velocity

MODEL: Parameter = $\beta_0 + \beta_1 \times$ Velocity $+ \beta_2 \times$ Velocity^2					
Parameter	β_0	β_1	β_2	R^2	RMSE[a)]
Fracturability	93872	-119	0.038	0.946	21.82
Hardness	254489	-323	0.103	0.944	63.46
Springiness	92.2	-0.118	0.38×10-4	0.797	0.06
Chewiness	44342	-56.1	0.018	0.833	17.49

[a)] Root mean square error

Table 3. Regression model to predict mechanical properties with attenuation coefficient

MODEL: Parameter = $\beta_0 \times$ Attenuation coefficient $^{\beta_1}$				
Parameter	β_0	β_1	R^2	RMSE[a)]
Fracturability	171002	6.371	0.650	73.23
Hardness	2028347	5.700	0.667	197.68
Springiness	8.90	1.832	0.620	0.09
Chewiness	5582010	7.898	0.603	35.86

[a)] Root mean square error

Table 4. Multivariate regression models for predicting texture properties of cheese

MODEL: Parameter = $\beta_0 + \beta_1 A + \beta_2 B + \beta_3 AB + \beta_4 A^2 + \beta_5 B^2$ [a]									
Parameter		β_0	β_1	β_2	β_3	β_4	β_5	R^2	RMSE[b]
Fracturability	coeff.	102939	-131.66	11044	-8.79	0.042	7861	0.949	21.12
	p-value	< 0.001	< 0.001	0.477	0.427	< 0.001	0.280		
Hardness	coeff.	300132	-387.14	60219	-42.77	0.125	23497	0.952	58.90
	p-value	< 0.001	< 0.001	0.165	0.165	< 0.001	0.235		
Springiness	coeff.	137.40	-0.181	58.71	-0.042	6×10-5	24.99	0.827	0.06
	p-value	0.001	0.002	0.179	0.172	0.002	0.203		
Chewiness	coeff.	40096	-50.0	-6209	3.30	0.016	2261	0.838	17.22
	p-value	0.001	0.003	0.623	0.712	0.006	0.695		

[a] A = Velocity, and B = Attenuation coefficient
[b] Root mean square error

variate linear regression analysis are listed in table 4. The R^2 and RMSE were better than those of the single ultrasonic parameter regression models. However, two models, i.e., multivariate linear regression model and single ultrasonic velocity regression model were not significantly different, suggesting that ultrasonic velocity is a sufficient parameter for measuring cheese texture properties. Also, results indicated that the texture properties of cheese were significantly related to the ultrasonic velocity rather than attenuation coefficient. Therefore, it is conclusive that the use of ultrasonic velocity would be more effective in the measurement of cheese texture instead of using both ultrasonic parameters.

Conclusions

A non-contact air instability compensation ultrasonic system was used to estimate the texture properties of five varieties of hard cheese as a function of ultrasonic velocity and attenuation coefficient, interpreting the data using statistical regression analysis. The 1 MHz longitudinal ultrasonic wave could be transmitted through cheese samples without contact. Of the ultrasonic parameters, ultrasonic velocity showed more significant relationship with cheese texture than ultrasonic attenuation coefficient. The texture properties could be estimated by the ultrasonic velocity regression model with the determination coefficients of 0.946 (RMSE = 21.82 N), 0.944 (RMSE = 63.46 N), 0.797 (RMSE = 0.06 ratio), and 0.833 (RMSE = 17.49 N) for fracturability, hardness, springiness, and chewiness, respectively. Owing to its non-contact, non-destructive, rapid measurement characteristics, the non-contact air instability compensation ultrasonic technique is an effective alternative to conventional cheese texture measurements.

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