Detection of foreign objects in milk using an ultrasonic system

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ABSTRACT

This paper presents the utilization of an ultrasonic sensing system to detect foreign objects in milk. The advantage of an ultrasonic system is that it is low cost and it can detect a wide range of materials. A foreign body is any contaminated object found in food. Because of the scale of multifarious food processing levels and distribution, the utilization of the food product are sometimes difficult to control, which will inevitably lead to some complaints by consumers. Milk is widely consumed in the world as it is considered as a healthy drink due to it is high nutrients levels. However, from time to time cases of milk contamination are reported. In this paper, the relationship between the foreign bodies in terms of their dimensions and the resultant amplitude are presented. Mathematical modelling were carried out based on two ultrasonic parameters i.e. acoustic impedance and wave amplitude utilizing several types of foreign bodies with different dimensions. Three types of foreign bodies which are steel, rubber and air were investigated to determine the voltage amplitude detected by the ultrasonic receiver when the foreign bodies obstructed the ultrasonic wave propagation path. The diameters of foreign bodies were in the range from 4 mm to 11 mm. The results showed good correlations between the receiver voltage and the size of foreign bodies with correlation coefficients greater than 0.95. Each foreign body also demonstrated different voltage amplitudes when several sizes of the foreign bodies were tested which showed the ability of the system to distinguish the size of each foreign body.

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1. INTRODUCTION

Milk contains a variety of vital compositions for human beings such as carbohydrate that provide energy to the body. It also provides a source of protein that can develop human muscle to be more healthy and strong. Moreover, milk is also loaded with calcium sources which can strengthen bones and protect against tooth decay. Dairy milk is exposed to be contaminated with various forms such as chemical, biological and physical substances [1]. It is said to be polluted by chemicals substance when the chemicals liquid exists during the manufacturing process such as oil from milk processing machines accidently spills into the milk tank. Milk is sometimes contaminated with biological materials such as E. coli and Salmonella bacteria via poor milking practices, soiled hands and soiled equipment. Contamination through physical substance occurs when foreign objects such as hair, steel, glass, plastic and rubber fragments accidently included in the processing machine and packaging container.

The existence of foreign objects in the milk product is a cause of concern ascan endanger human health [2]. The colour of milk is not transparent and it is produced in a variety of flavours such as chocolate, strawberry, full cream and fresh milk. Therefore, it is difficult to see by the naked eye if there is any foreign object in the milk. If lucky, we will be able to distinguish the foreign body when it floats on the surface of the milk when the milk is poured into the cup. In addition, the knocking noise also can be heard when the foreign body hitting the cup when pouring process. The consumers are exposed to risk if the milk is drink directly from the milk carton or using a straw. This paper presents the application of ultrasonic sensor to detect the foreign body in milk cartons. In detecting foreign objects, an ultrasonic system has the advantages of being inexpensive and non-intrusive. As such the objects of interest are not damaged. Ultrasonic sensors are widely applied in food industry since it offers a non-destructive way to inspect the product [3, 4]. Ultrasonic has been successfully been applied for freezing, cavitation, emulsification and thermosonication for many types of food products [5–7]. Several investigationson foreign body detection using ultrasonic sensor had been carried out as reported by Correia et al [8], Zhao et al [9], Pallav et al [10],Leemans and Destain[11], Tantray et al [12] and Polat et al [13], Mcclements [14],Hassler and Homayoon [15], Le Coz et al [16],Iuliano [17], Liu et al [18], Liaw et al [19], Makinde et al [20], Holmes et al [21], Melo et al [22], Khan et al [23], Prabhakar et al [24],Rodrigues et al [25], Franchini et al [26], Pandey [27], Aftab et al [28], Gounder and Tan [29], Sadaka et al [30], Fasina et al [31], Khan et al [32], Mitev et al [33], Roux et al [34], Nakib et al [35], Rathore [36], Singleton et al [37], Mahesh et al [38], Ezenwa [39], Natung [40] and Mustapha [41], In this paper, two common foreign bodies materials e.g. steel and rubber with different sizes were used to investigate the sensor voltage and voltage loss at the ultrasonic receiver. The mathematical modelling was studied using two parameters which commonly applied in ultrasonic measurement which is acoustic impedance and amplitude wave. Air medium was used to compare with the metal and the rubber materials since the air has the lowest acoustic impedance which is 0.00041×10^6 kg/m^{2}s.

2. MATHEMATICAL MODELLING

This section consists of two modelling of parameters that related to the ultrasonic acoustic properties which are acoustic impedance and amplitude wave. Some assumptions have been used in the modelling and experiment. First, the round shape is selected as a foreign body's shape. Next assumption is the energy losses between ultrasonic transducer and couplant is assumed to be zero.

The acoustic impedance is another parameter that must be considered in the ultrasonic interaction concept. The acoustic impedance is expressed as:

$$Z = \rho c \qquad (1)$$

whereρ is the density of the material (kg/m^3) and c is the sound velocity of the material (m/s). The transmission and reflection coefficients of a wave are calculated based on the following equations:

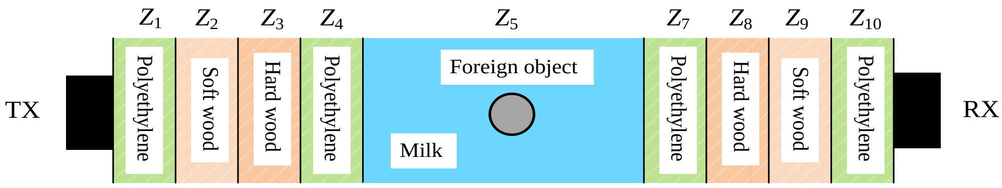
$$\text{Reflection coefficient, } R = \left(\frac{Z_2 - Z_1}{Z_2 + Z_1}\right)^2 \qquad (2)$$

$$\text{Transmission coefficient, } T = \frac{4Z_1 Z_2}{(Z_1 + Z_2)^2} \qquad (3)$$

whereZ_1 and Z_2 are the acoustic impedances for material 1 and material 2 respectively. The modelling for several materials such as milk carton and foreign body material are investigated. The values of density, speed of sound and acoustic impedance for the materials are tabulated in Table 1 and Figure 1 shows the interlayers of materials regarding the acoustic impedance of the ultrasonic wave. Milk carton consists of three different layers which is polyethylene, soft wood and hard wood. The thickness of each layer has a range from 0.1 mm to 0.3 mm.

Table 1. The Values of Density, Speed of Sound and Acoustic Impedance for Materials [14]

Material	Density, ρ (kg/m^3)	Speed of sound, c (m/s)	Acoustic Impedance, Z ($\times 10^6$ kg/m^{2}s)
Polyethylene	900	1950	1.76
Wood (soft)	450	3600	1.62
Wood (hard)	850	3850	3.27
Milk	1037	1548	1.61
Rubber	1200	1600	1.92
Steel	7850	5790	45.45
Air	1.2	343	0.00041



TX, RX = Transmitter, Receiver
Z_1, Z_4, Z_7, Z_{10} = Acoustic impedance for polyethylene
Z_2, Z_9 = Acoustic impedance for wood (soft)
Z_3, Z_8 = Acoustic impedance for wood (hard)
Z_5 = Acoustic impedance for milk
Z_6 = Acoustic impedance for foreign object

Figure 1. The interlayers materials regarding the acoustic impedance of the ultrasonic wave

The transmission and reflection coefficient at each boundary and material were determined using (2) and (3) and the results are presented in Table 2. In boundary 1 until boundary 4, the ultrasonic wave experienced more transmission than reflection by 98.72%, 87.89%, 91.20% and 99.70% respectively. Thus, the wave energy does not significantly decrease during propagating in these boundaries. However, the wave experienced more reflection by 99.90% and 86.80% when the air and steel are designated as a foreign body. On the other hand, the ultrasonic wave just shows 0.77% of reflection when the rubber is used as foreign body.

Table 2. The Reflection and Transmission Coefficients in Percentages

Boundary	Condition	Reflection (%)	Transmission (%)
1	Polyethylene to wood (soft)	1.28	98.72
2	Wood (soft) to wood (hard)	12.11	87.89
3	Wood (hard) to polyethylene	8.80	91.20
4	Polyethylene to milk	0.30	99.70
5	Milk to polyethylene	0.30	99.70
6(i)	Milk to foreign body (air)	99.80	0.20
6(ii)	Milk to foreign body (rubber)	0.69	99.31
6(iii)	Milk to foreign body (steel)	87.10	12.90
7	Polyethylene to wood (hard)	9.20	90.80
8	Wood (hard) to wood (soft)	11.23	88.77
9	Wood (soft) to polyethylene	0.15	99.85

The analysis of the amplitude wave is a simple approach to determine whether the milk contains any foreign body or not. The transmitted wave has a certain wave energy level that should be detected by a receiver. The foreign body size has influenced the level of amplitude wave. The larger size of the foreign body led to more reduction in the amplitude due to the wave being blocked from propagating to the receiver. The level of voltage at the receiver can determine the correlation between the size and amplitude wave as illustrated in Figure 2. The size of ultrasonic sensor used in this study is 13 millimeter (mm) and the transmitter voltage is 4.8 Volt (V). The equation for the receiver voltage equation is written as [42]:

$$V_R = V_T - V_d \quad (4)$$

$$\frac{V_R}{V_T} = \frac{d}{13} \quad (5)$$

$$V_R = {}^{d}/_{13} \times V_T \quad (6)$$

As shown in (6) is inserted into (4) to get:

$$V_R = V_T - \left[{}^{d}/_{13} \times V_T\right] \quad (7)$$

$$V_R = 4.8 - \left[{}^{d}/_{13} \times 4.8\right] \quad (8)$$

where V_R is the receiver voltage, V_T is the transmitter voltage, V_d is the voltage loss when there is a foreign body between the transmitter and the receiver.

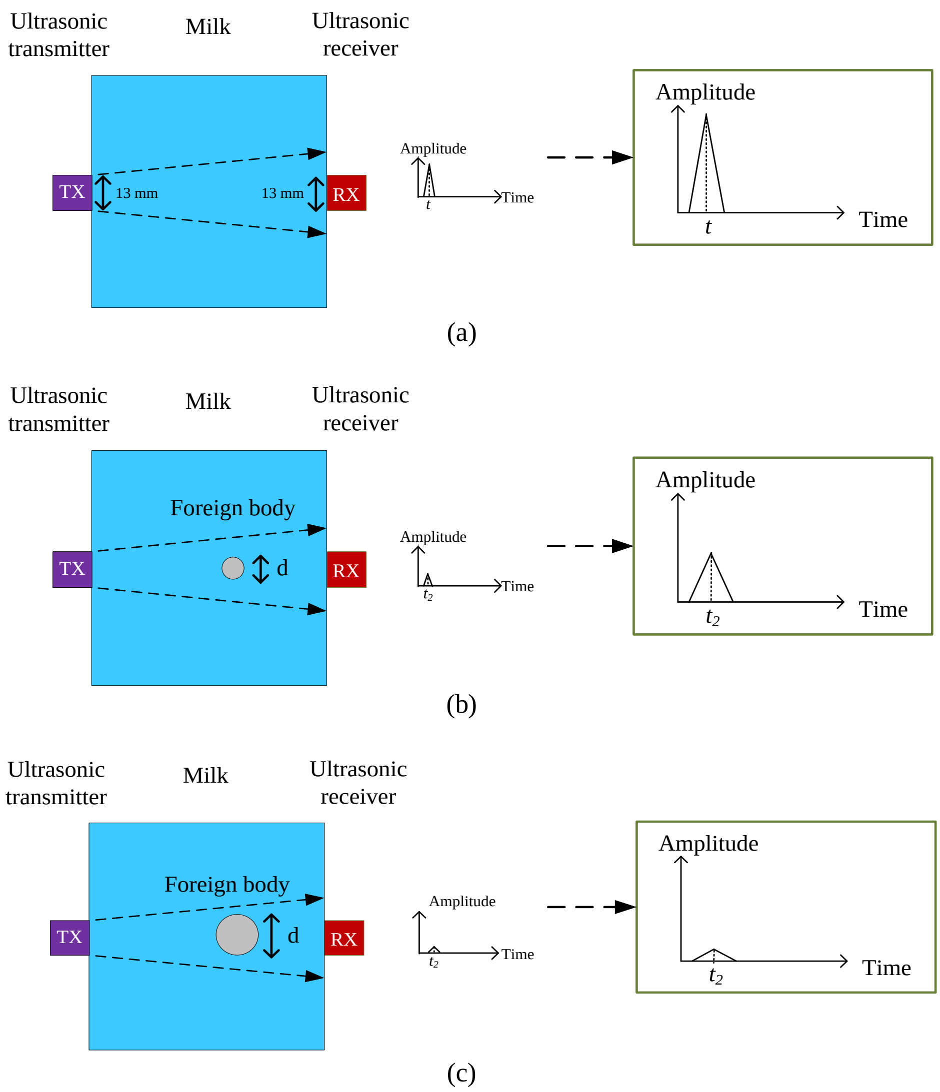


Figure 2. Predicted amplitudes for different sizes of foreign bodies

3. EXPERIMENTAL SETUP

Two ultrasonic sensors model MCUSD13A300B09RS developed by Multicomp were used as transcceivers. The sensors have a center frequency of 300 kilohertz (kHz), diameter of 13 mm and the length is 9 mm. It has 10° of angle beam and the sensor is covered by aluminum case. The transmitter and receiver circuit were driven by 12 Volt (V) from direct current power supply and a port from Peripheral Interface Controller (PIC) microcontroller model PIC18F4520 was used to generate the pulse signal to transmitter circuit. The wave signal was evaluated and measured using an oscilloscope. The transmitter and the receiver were placed outside of a milk carton which the carton has a cross sectional size of 7.3 mm × 7.4 mm. The experiment was conducted using pasteurized chocolate milk manufactured by Dutch Lady under the condition of 24°C for milk and room temperature. The experimental setup for the ultrasonic measurement is illustrated as in Figure 3.

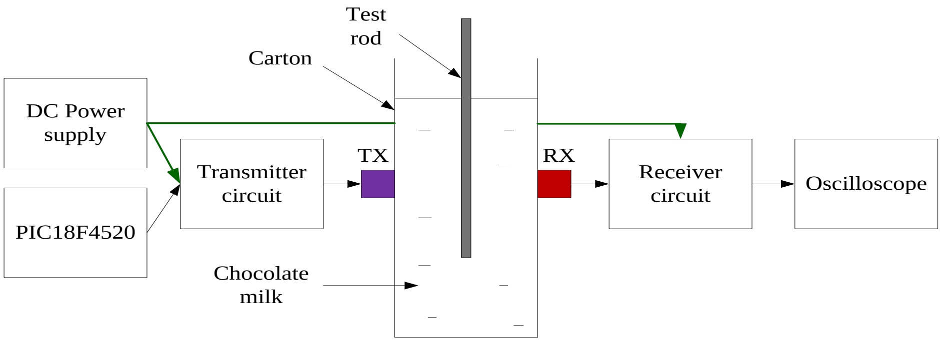
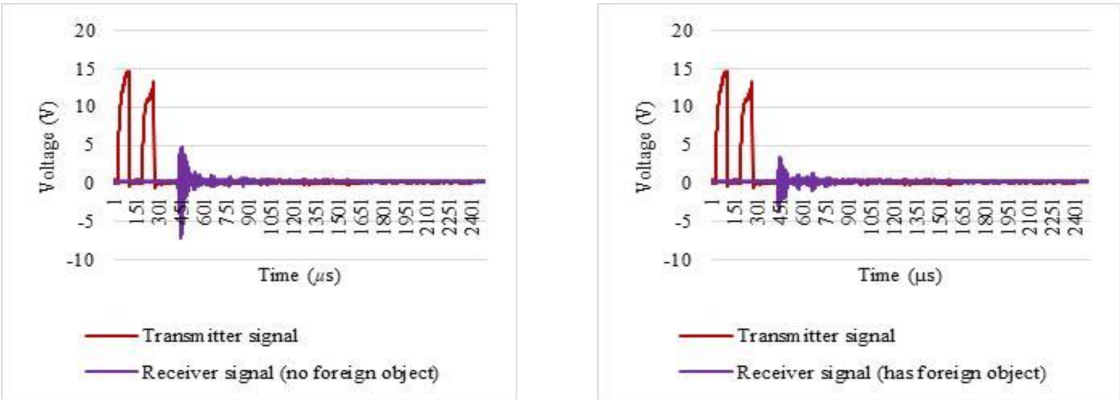


Figure 3. The experimental setup for ultrasonic measurement

4. RESULTS AND DISCUSSION

This section comprises the experimental results and the discussion. In the experimental work, two types of voltage were investigated which are the receiver voltage and the voltage loss. Both theoretical and experimental voltages were calculated based on (6) and (8) for determining the correlation between three different materials of foreign bodies; air, steel and rubber. Several sizes of rods for each material had been used where the diameters of the rods were from 4 mm to 11 mm. The example of waveforms for the non-existence and existence of foreign object are shown in Figure 4(a) and Figure 4(b), respectively where a steel rod with diameter of 7 mm was used as the foreign object.



(a) (b)

Figure 4. The ultrasonic waveform (a) Non-existence of foreign object (b) Existence of foreign object

The correlation between the size and foreign body's materials were analyzed using linear regression analysis. A linear regression line has an equation of the form $Y = a + bX$, where X is the explanatory variable and Y is the dependent variable. The value of a, b and correlation coefficient (r) is calculated using (9), (10) and (11), respectively where x and y are plenty of data, n is total sample data, $\bar{x}$ is mean of x data and $\bar{y}$ is mean of y data. The results of the receiver voltage and voltage loss were presented in Table 3 and plotted graphically in Figure 5 and Figure 6. The linear regression equation and the value of regression coefficient for receiver voltage and voltage loss are presented in Table 4 and Table 5.

$$a = \frac{(\sum y)(\sum x^2) - (\sum x)(xy)}{n(\sum x^2) - (\sum x)^2} \quad (9)$$

$$b = \frac{n(\sum xy) - (\sum x)(y)}{n(\sum x^2) - (\sum x)^2} \quad (10)$$

$$r = \frac{\sum_{i=1}^{N}(x_i - \bar{x}_i)(y_i - \bar{y}_i)}{\sqrt{(\sum_{i=1}^{N}(x_i - \bar{x}_i)^2)(\sum_{i=1}^{N}(y_i - \bar{y}_i)^2)}} \quad (11)$$

Table 3. Theoretical and Experimental Results

Diameter, *d* (mm)	Theoretical Predicted		Experimental Air		Experimental Steel		Experimental Rubber	
	Receiver voltage, V_R (V)	Voltage loss (V)	Receiver voltage, V_R (V)	Voltage loss (V)	Receiver voltage, V_R (V)	Voltage loss (V)	Receiver voltage, V_R (V)	Voltage loss (V)
11	0.738	4.062	0.800	4.000	2.000	2.800	3.000	1.800
10	1.108	3.692	1.400	3.400	2.300	2.500	3.200	1.600
7	2.215	2.585	2.200	2.600	3.400	1.400	3.400	1.400
5	2.954	1.846	3.400	1.400	3.800	1.000	4.000	0.800
4	3.323	1.477	3.600	1.200	4.000	0.800	4.300	0.500

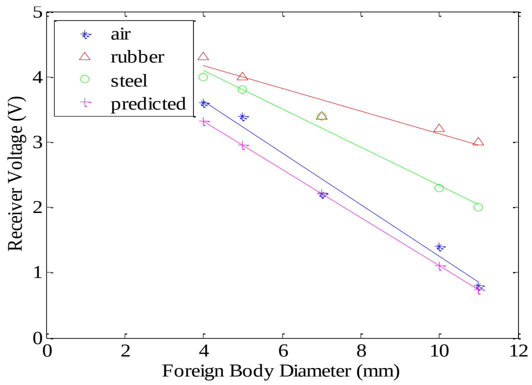


Figure 5. The correlation graph between foreign body diameter and receiver voltage

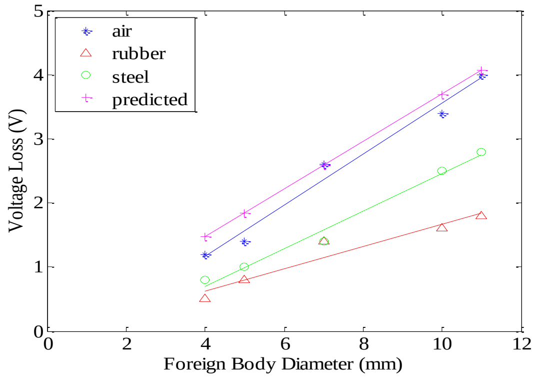


Figure 6. The correlation graph between foreign body diameter and voltage loss

Table 4. The Regression Equation and Correlation Coefficient for Receiver Voltage

Material	Regression equation	Correlation coefficient, *r*
Ideal	y = -0.3693x + 4.8001	1
Air	y = -0.3968x + 5.2161	0.9906
Steel	y = -0.293x + 5.2683	0.9928
Rubber	y = -0.1737x + 4.8651	0.9637

Table 5. The Regression Equation and Correlation Coefficient for Voltage Loss

Material	Regression equation	Correlation coefficient, *r*
Ideal	y = 0.3693x - 7E-05	1
Air	y = 0.3968x - 0.4161	0.9906
Steel	y = 0.293x - 0.4683	0.9928
Rubber	y = 0.1737x - 0.0651	0.9637

4.1. Discussion

Both receiver voltage and voltage loss showed the same correlation coefficient for all foreign bodies materials. The level of receiver voltage is decreased when larger diameter of foreign body is placed between the transmitter and receiver sensor. Each material also shown the different level of receiver voltage due to the different acoustic impedances value. Steel material showed the lower voltage compare to the rubber materials for all diameter size. This situation verified that the wave has reflected away with 86.80% compared to 13.20% for transmission (as calculated in section 2.1) when it propagating through the steel material. Hence, the amplitude of wave energy is decreased when it reached at receiver sensor. The air medium had been tested as a foreign body to observe and compare the different consequence between steel and rubber. As expected, the air medium showed the minimum receiver voltage and the maximum voltage loss for all diameter of foreign body. The result has obeyed the theoretical calculation as studies in section 2.1 where the air medium has the smallest acoustic impedance with 0.00041 × 10^6 kg/m^2s compare to other materials. All materials showed greater than 0.95 for correlation coefficient and proved that the ultrasonic sensor can detect the foreign objects.

5. CONCLUSION

This paper presents the modelling and experimental work to investigate the linearity of ultrasonic sensor for detecting the foreign body in milk product. The modelling comprises of two parameters which are acoustic impedance and amplitude wave. The lowest transmission coefficient was shown when the ultrasonic wave propagated from milk to air medium with 0.10 %, followed by steel material with 13.20% and rubber with 99.23%. The linear model for amplitude wave was calculated and the results for both theoretical and experimental plots has been obtained. This research shows that the ultrasonic sensor can determine the materials and size of foreign body contain inside the milk cartons using non-destructive method and beneficial in the field of food safety and quality assurance.

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