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Fuzzy On-Line Monitoring System for Yogurt Fermentation Using Ultrasonic Characteristics

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Abstract— Fermentation is the process where bacteria convert lactose to lactic acid. When milk is fermented to make yogurt, its elasticity increases accordingly. pH meters have traditionally been used for fermentation process monitoring based on acidity. Ultrasonic systems can provide a rapid, accurate, inexpensive, simple and non-destructive method to on-line monitor the properties of food during process operations. This paper evaluates the use of ultrasonic measurements to characterize yogurt fermentation process by correlating acoustic properties and fermentation process characteristics. This research shows the correlation between fermentation time and acoustic attenuation as well as acoustic velocity. It also shows the effect of temperature on the received signal attenuation and velocity for yogurt and milk. This paper also proposes a fuzzy logic inference system to model the yogurt fermentation process. The relative peak to peak amplitude and the relative time of flight are used as an input to the fuzzy inference system.

Keywords— Fuzzy logic, Sound attenuation, Sound velocity, Ultrasound, Yogurt fermentation.

I. INTRODUCTION

Ultrasonic (US) sensors are proved to be effective in many industrial and medical applications. Most known are nondestructive testing (NDT) and ultrasonic imaging. Ultrasonic sensors are used as flow and level meters in the process industry. Recently, new fields of ultrasonic sensor technology have emerged and partly improved transducer development and signal processing [1], [2], and [3]. Technology road map points out that ultrasonic will be among the emerging techniques to solve future problems in process control [4]. Ultrasonic characteristics are used for non-invasive process control by correlating sound parameters and characterizing process parameters. One specific and challenging application is the analysis of liquid multi-phase mixtures like suspensions, emulsions and dispersions [5]. Ultrasonic sensor systems are used instead of industrial chemical sensors because of their fast response, robustness and reliability.

Sound velocity, sound absorption and acoustic impedance can be applied as acoustic properties together with advanced signal processing to measure liquid mixture properties and continuously control and monitor processes [6]. Ultrasonic measurement is based on the change in the properties of the transmitted acoustic wave, which is influenced by the medium [7] shown in Fig. 1. The information needed to characterize fluid media in time and space is contained in the transmitted or reflected ultrasonic waves [3]. This kind of measurement is indirectly affected by other unwanted phenomena [3]. Ultrasonic sensors and their advantages, disadvantages are discussed in [8]. Henning describes the state of technology in the field of the computer-assisted ultrasonic transducer development and its limits [9].

This paper verifies the use of the two basic sound parameters (velocity, attenuation) for yogurt fermentation process monitoring and control. It also proposes a fuzzy logic inference system to model the yogurt fermentation process. The relative peak to peak amplitude and the relative time of flight are used as an input to the fuzzy inference system. This research aims to

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automate the whole butter churning process [10]. This paper is an extension of the work originally reported in Proceedings of the International Conference on New Developments in Circuits, Systems, Signal Processing, Communications and Computers [11].

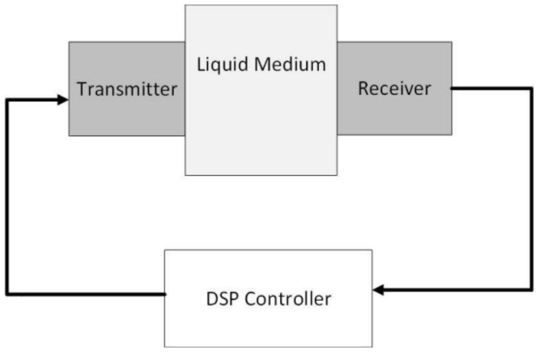

Fig. 1. Generic ultrasonic system block diagram

II. Yogurt Fermentation

Technological innovation is one of the drivers of the increased payoffs for the dairy industry [12]. Productivity control and high product quality insurance of fermented milk products can be achieved only by in-line monitoring of the fermentation process. This leads to an evolving interest in the development of cheap reliable control systems to monitor fermentation process in industry. Because fermentation is a complex process, it is hard to predict the time of incubation. Usually the pH value defines the end point of incubation. The pH meter has been used for fermentation process monitoring based on acidity [13]. Extensive cleaning and calibration make pH measurement not preferred for on-line monitoring. The pH end point of incubation is 4.4 to 4.5. PH is the most useful value characterizing the fermentation process. However, pH sensors need a regular calibration and maintenance. The pH probe is considered unreliable for fermentation monitoring under industrial conditions. The pH, electrical conductivity, emitted gases, optical spectroscopy and viscosity can be used for fermentation monitoring as shown in Table 1. Most of fermentation processes are off-line monitored as a consequence of unreliable high-cost control systems based on the sensors shown in Table 1.

Ultrasonic systems are increasingly being used in the dairy industry. Butter has traditionally been made of yogurt. When a sufficient amount of milk is collected, it is fermented and churned by shaking until butter granules are formed. Fermentation is the process where sugars are transformed into lactic acid. Ultrasonic systems can provide a rapid, accurate, inexpensive, simple and non-destructive method to on-line monitor the properties of food during process operations. Ultrasonic is not an off-the-shelf technology. Thus, it needs to be developed and scaled up for each application. Ultrasonic sensor systems can be utilized to continuously monitor fermentation and churning processes to allow for in-line control of the process. For example, ultrasonic sensor has the capability to replace pH sensor in the fermentation process. It can also be used to represent the relationship between pH, conductivity or density and the progress of the churning process. This can be implemented by utilizing artificial intelligence as well as digital signal processing techniques [14].

I. Experiments and Materials

Two ultrasonic transducers have been used as a transmitter and receiver as shown in Fig. 2. A 1 MHz 5-period burst has been generated (AWG 520, Sony Tektronics) and amplified to 10 V (AR 75A520, Amplifier Research) before transmitting it through the milk (transmitter:

Olympus Panametrics V302, receiver: Pico 1.2, Physical Acoustics Corp., Princeton, USA). Alignment has been performed with 3D stages (Newport). An oscilloscope (wavepro 700, LeCroy) has been used to obtain the time of flight which is the time taken by the ultrasonic pulse to travel through the milk. A double-jacket vessel contains the sample. Temperature has been maintained by a temperature controller with an accuracy of 0.1 K. A stirrer has been used for proper shaking and homogenization. The homogenized and fresh milk and plain yogurt were purchased from the local grocery store, Magdeburg, Germany. Raw milk has been provided by Wanke Agrar GmbH, Cobbel, Germany. Plain yogurt was used as the yogurt starter culture. The fermentation has been performed with 400 cc of milk and 40 cc of yogurt starter at 40° C.

TABLE 1
TYPE OF SENSORS USED FOR ON-LINE MONITORING OF YOGURT FERMENTATION PROCESS

Sensing Group	Sensor Type	Sensor	Reference
Electrical	Electrode conductance	Conductivity	[15], [16]
Chemical	Gas (odor-sensitive)	Electronic noses (EN) and tongues	[17]
	pH	pH	[16], [18]-[22]
	Viscosity		[19]
	Gas (Array of sensor)	DO_2, O_2, CO_2	[20], [21]
Optical	Spectroscopy	Near-infrared (NIR) spectroscopy	[14], [15], [23]-[27]
	Spectroscopy	Middle-infrared	[25], [28]
	Spectroscopy	UV, IR, and fluorescence	[29]
Mechanical	Vibrating rod	Viscosity	[30]
Multi	Multi sensor	NIR spectrometry and EN	[31], [32]

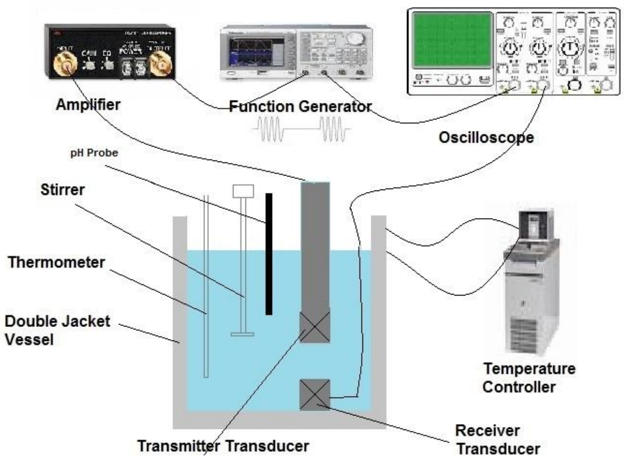

Fig. 2. Experimental setup

The ultrasonic velocity was calculated dividing the distance between the transmitter and receiver transducer by the time of flight. The received ultrasonic peak to peak amplitude is measured by the oscilloscope. A pH probe (oMX 3000, WTW Weilheim, Germany) has been used for the on-line measurement of yogurt acidity.

II. Results and Discussion

A. Acoustic Attenuation

Relative peak to peak amplitude is used to measure the change in the amplitude relative to the peak to peak amplitude at the beginning of the fermentation process. Absolute attenuation is not used because it depends on many other factors. Relative peak to peak amplitude provides remarkable information for monitoring the change in the yogurt fermentation process. Correlation was found between acoustic attenuation and the fermentation process as shown in Fig. 3. These findings can directly be used to model the yogurt fermentation process. pH values are determined during the fermentation process as shown in Fig. 4. pH decreases with fermentation as attenuation does. The slope of attenuation is very similar to the slope of the relation of pH with the fermentation time. Some distinct differences larger than the confidence range need further analysis. Hence, relative attenuation can be used to monitor the fermentation process as a replacement for pH measurement.

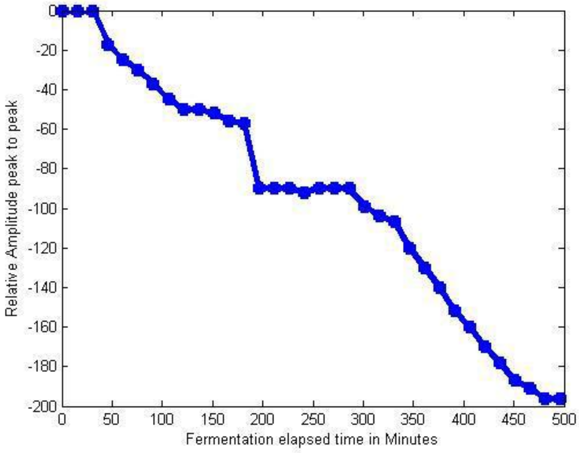

Fig. 3. Relationship between the amplitude of the received signal and the fermentation time

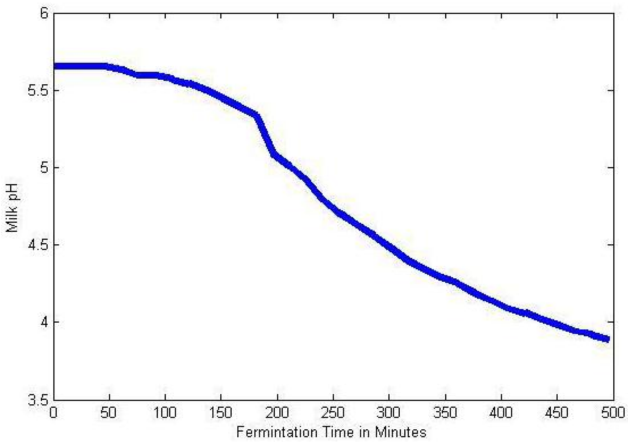

Fig. 4. pH measured using a pH meter

Care should be taken when measuring the amplitude of the received signal. An opposite relation could be measured if the stirrer is used in high speed. We assume water can be separated from milk although it could not be observed visually. The ultrasonic waves going through water should cause an ultrasound amplitude increase with the fermentation process as shown in Fig. 5 with the stirrer at high speed.

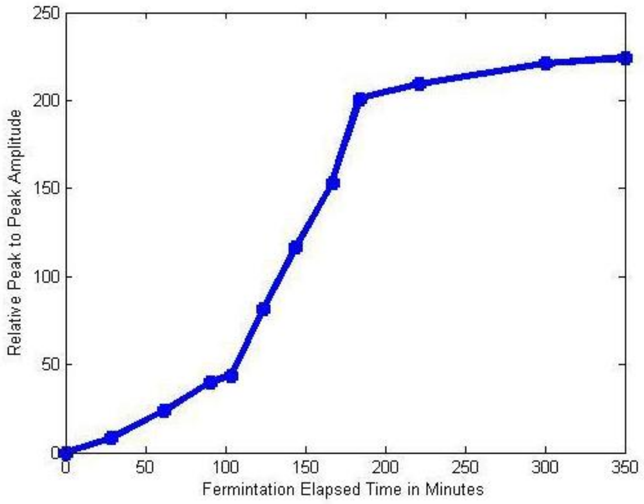

Fig. 5. Relationship between the amplitude of the received signal and the fermentation time when a stirrer is used

B. Acoustic Velocity

Relative time-of-flight is considered in this research with setting time-of-flight to zero at the beginning of the experiment. In this way, uncertainties in alignment and effective distance between transducers are compensated. Fig. 6 shows a remarkable correlation between the relative time of flight and the fermentation process. The time-of-flight measurements, however, have not been affected when a stirrer is used at high speed. The ultrasound velocity increases with the fermentation process.

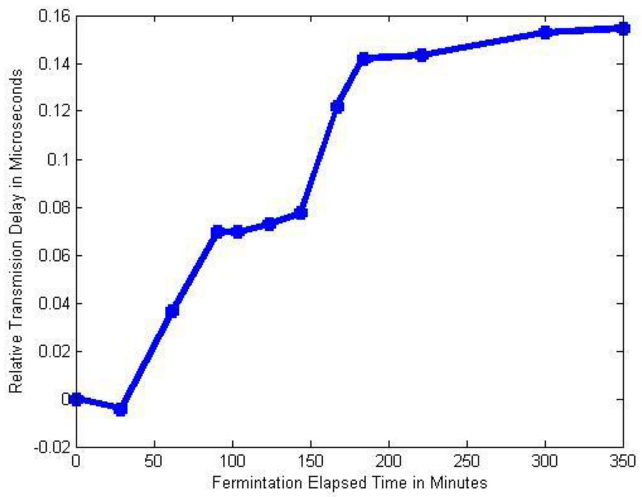

Fig. 6. Relationship between the relative time of flight and fermentation time

All the experimental results displayed in Figs. 3-6 are the average of a set of experiments under the same conditions. Moreover, when keeping the milk in a fridge below 10° C, we did not find a systematic tendency within several days.

C. Discussion

Our first steps toward a real-time, on-line, non-contact monitor of the fermentation process with ultrasound have shown an adequate relation between attenuation and speed of the sound with the fermentation time. Both acoustic characteristics can, therefore, be used to monitor the fermentation process. However, the difference in the amplitude between the start and the end of fermentation is quite bigger and smoother than the time of flight. The second advantage of the amplitude measurement is that it does not depend on the temperature as shown in Fig. 7; yet, Fig. 8 shows an effect of temperature on the sound speed of yogurt and milk. However, amplitude measurement is affected by alignment and effective distance between the transducers. It is also more affected by air bubbles than the time of flight. Thus, this paper proposes a fuzzy system that combines both the ultrasonic amplitude and the time of flight to model the fermentation process.

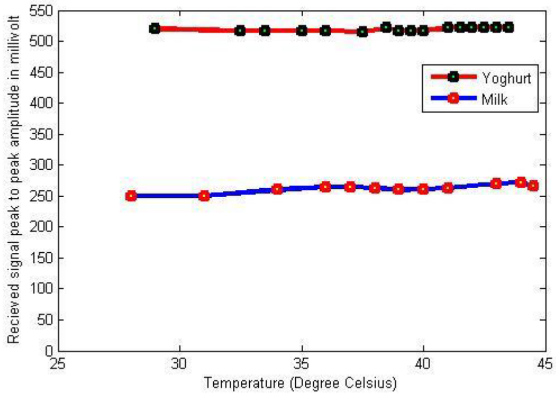

Fig. 7. Temperature effect on the received signal attenuation for yogurt and milk

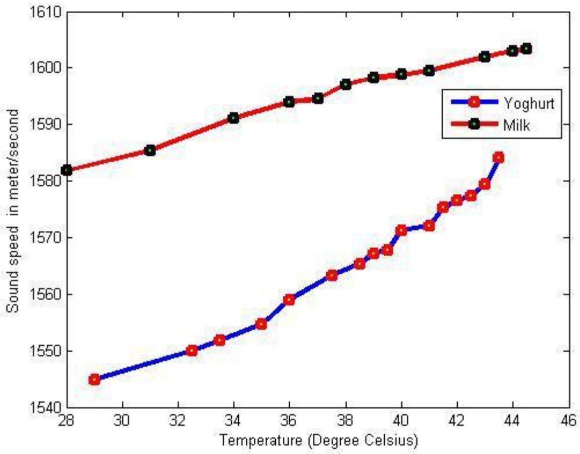

Fig. 8. Temperature effect on the sound speed of yogurt and milk

D. Fuzzy Inference Modeling System

Fuzzy logic inference is a simple approach to solve a problem rather than attempting to model it mathematically. Empirically, the fuzzy logic inference depends more on human experience than the technical understanding of the problem. Fuzzy logic inference consists of three stages:

1. Fuzzification: map any input to a degree of membership in one or more membership functions. The input variable is evaluated in term of the linguistic condition.
2. Fuzzy inference: fuzzy inference is the calculation of the fuzzy output.
3. Defuzzification: defuzzification is to convert the fuzzy output to a crisp output. In this paper, the output is calculated based on Mamdani defuzzification technique.

The main idea of this paper is to recognize the ultrasonic characteristics used to characterize the yogurt fermentation process. The relative peak to peak amplitude and the relative time of flight are used as an input to the fuzzy inference system. In this paper, the selection and formulation of the input and output fuzzy sets and their membership functions are based on expert knowledge. The first input is the relative peak to peak amplitude of the received ultrasonic signal. The corresponding fuzzy values are defined to be Very Low (VL), Low (L), Medium (M), High (H) and Very High. Membership functions are shown in Fig. 9. The second input is the relative time of the flight of the ultrasonic signal. The corresponding fuzzy values are defined to be Very Low (VL), Low (L), Medium (M), High (H) and Very High (VH). The corresponding membership functions are shown in Fig. 10. Finally, the output of the system is the fermentation degree, which is defined by four fuzzy values: Zero (Z), Low (L), Medium (M), High (H) and Full (F). Membership functions are shown in Fig. 11. The whole mapping process is shown in Fig. 12, where MATLAB fuzzy toolset is used. The input and output membership functions as well as the fuzzy rules were tuned manually based on the real test data and number of experts. Table 2 summarizes the fuzzy rules.

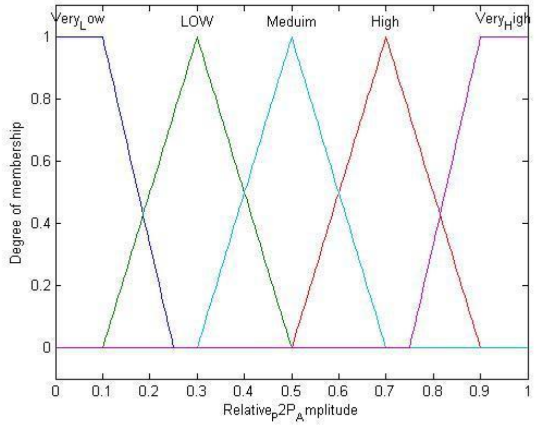

Fig. 9. Input one membership functions

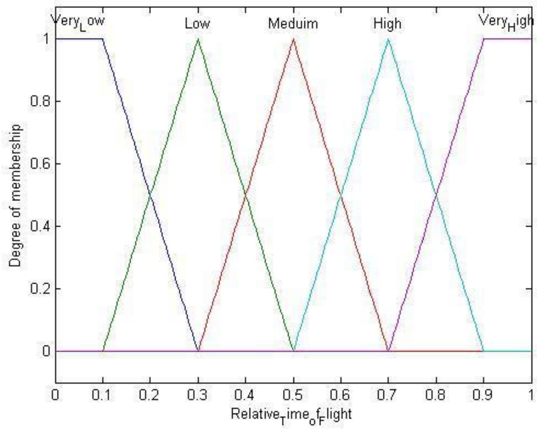

Fig. 10. Input two membership functions

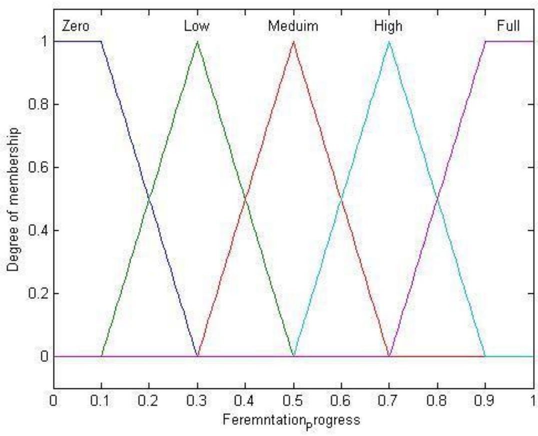

Fig. 11. Output membership functions

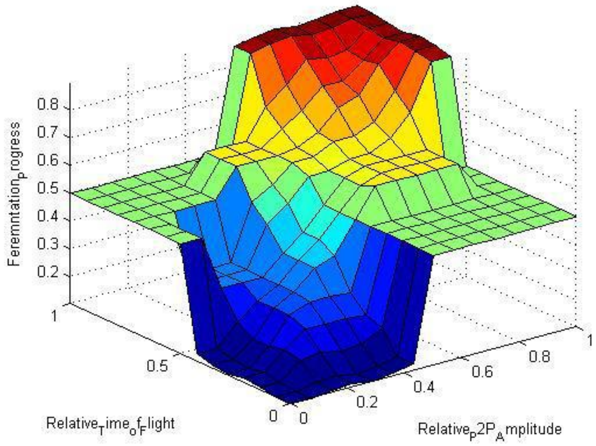

Fig. 12. Fuzzy Service

TABLE 2
FUZZY RULES

Input 1 / Input 2	Very Low	Low	Medium	High	Very High
Very Low	Zero	Zero	Low	Medium	Medium
Low	Zero	Low	Low	Medium	Medium
Medium	Low	Low	Medium	Medium	high
High	Medium	Medium	Medium	High	Full
Very High	Medium	Medium	High	Full	Full

III. CONCLUSIONS AND FUTURE WORK

Relative amplitude attenuation and the time of ultrasonic flight are measured during the yoghurt fermentation process. Correlation was found between acoustic characteristics and the fermentation process. During the fermentation, acoustic attenuation and velocity change due to a change in the nature of the crossed middle. Results showed that relative ultrasonic measurements (velocity and attenuation) can be used to characterize the yogurt fermentation process. The amplitude measurement is less dependent on temperature than the ultrasonic velocity measurement. Stirring at high speed can have a big effect on the ultrasonic measurement of the fermentation process; we assume that water and milk are separable but not the air bubbles. This finding has to be considered for future work, where the ultrasonic measurement will be evaluated for the butter churning process which requires stirring. A fuzzy logic inference system can be used to model the yogurt fermentation process, where relative peak to peak amplitude and the relative time of flight are used as inputs to the fuzzy inference system.

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