Fuzzy Ultrasonography System for Estimating Roughness by Using 1MHz Probe

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***Abstract*— A surface roughness of the cartilage estimation is important in diagnosis of the osteoarthritis of a knee. However, the estimation method for surface roughness of the cartilage has not been established. This paper proposes a fuzzy rule-based system for estimating the surface roughness by ultrasonic waveform. The final goal is to diagnose osteoarthritis of the knee. Our estimation method consists of three steps. The first step extracts characteristic values from an object with known surface roughness. The second step constructs fuzzy membership functions with respect to characteristic values and the estimation system of the surface roughness. At the final step, the fuzzy rule-based system estimates the surface roughness of an object with unknown surface roughness. We applied this method to phantoms having three kinds of surface roughness, where, eight samples per a surface (total twenty four samples) are used. Then, our system can successfully estimate all samples.**

I. INTRODUCTION

A surface roughness of the cartilage estimation is important in diagnosis of the osteoarthritis of a knee with progress of regenerative medical technology. The cartilage in the knee plays an important role to absorb a shock. However, the cartilage is worn out by increasing age and a physical factor. Then, the patients have the ache in the knee joint, which is called the osteoarthritis of knee, and a surface of the diseased cartilage becomes rough. Therefore, the evaluating the surface roughness degree of the cartilage contributes to diagnose the cartilage. Generally, Physician has evaluated the surface roughness of the cartilage by using the arthroscopy. However, it is difficult to quantitatively evaluate the roughness. For that reason, the quantitative evaluation technique of the surface roughness has been required. The diagnosis of the living body using an ultrasonic wave has some advantages, such as noninvasiveness, small equipment and the bedside usage. Therefore, estimating the surface roughness of the cartilage using an ultrasonic wave contributes to the quantitative evaluation of the surface roughness. High frequency probe has high resolution. However, high frequency ultrasonic wave is very attenuated in a bone. Low frequency ultrasonic wave (in this paper, 1MHz probe is used) can acquire echo data through the bone. Therefore, we use low frequency probe to estimate the surface roughness. Many researchers have studied the property of the echo using the ultrasonic wave for clinical applications [1]-[3]. Hattori et al. discuss the relationship between the surface roughness of cartilage and the characteristic values of ultrasonic echo from cartilage [4]. They showed that the surface roughness was related to the echo duration and the maximum amplitude as the characteristic values. However, they did not estimate the surface roughness by this relationship.

The purpose of this study is to estimate the surface roughness. In this paper, we propose a fuzzy rule-based system [5]-[8] for estimating the surface roughness by the ultrasonic waveform. The property of the echo varies in a degree of the surface roughness. Therefore, our method uses characteristic values of the echo for estimating the surface roughness of an object. Since the surface roughness of the object estimated by using characteristic values of one point echo data include wide variance. Our method employs average characteristic values of several points of echo data. Our method has thus established high robustness to a variance of characteristic values. The proposed method consists of three steps. In the first step, we extract two characteristic values from some phantoms having different surface roughness, where these surface roughnesses are known. The characteristic values are defined as the echo duration and the maximum amplitude. The second step constructs fuzzy membership functions with respect to characteristic values. If the echo duration value becomes higher and the maximum amplitude value becomes lower, then the surface becomes rougher. Fuzzy membership functions are constructed with this knowledge. In the final step, our method estimates the surface roughness of unknown data.

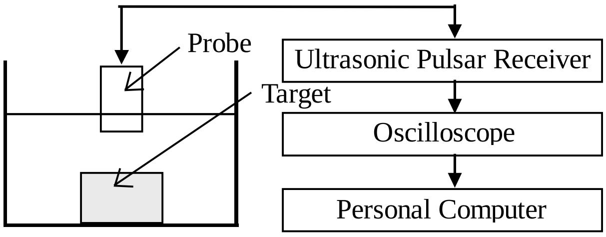

Fig. 1. Ultrasonic waveform acquisition system .

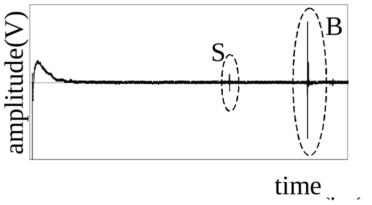

Fig. 2. An example of the acquired ultrasonic wave.

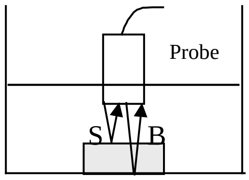

Fig. 3. Traveling paths of ultrasonic wave.

This study conducts experimentation using the phantom that similar to body tissue in acoustic characteristics. The proposed method is applied to the phantoms having three kinds of surface roughness, eight samples per a surface roughness (total twenty four samples) are used. Then, our system can successfully estimate all samples.

II. PRELIMINARIES

A. *Ultrasonic Waveform Acquisition System*

Fig. 1 shows the overview of our experiment system. The probe (1K14I/6I-F NYSI0030 21662) with 1 MHz center frequency is used. An ultrasonic wave is transmitted and received with an ultrasonic pulsar receiver (NEW SENSER Inc., NSI-PL01) via the probe, and an ultrasonic waveform is acquired with an oscilloscope (YOKOGAWA Electric Corp., DL1720CL). Moreover, the sampling interval is 0.01 μs, and data is acquired 100 μs. The scan area is *x* direction M mm and *y* direction N mm, and the number of the sampling points is M × N. The length from Probe to Target is 28 mm.

B. *Ultrasonic Waveform*

Fig. 2 illustrates an example of the acquired ultrasonic wave, and Fig. 3 illustrates traveling paths of the ultrasonic wave. In these figures, S means the echo from the surface of the target, and B means the echo from the bottom. In this paper, S and B are called the surface echo and the bottom echo, respectively. In this study, surface echo is analyzed.

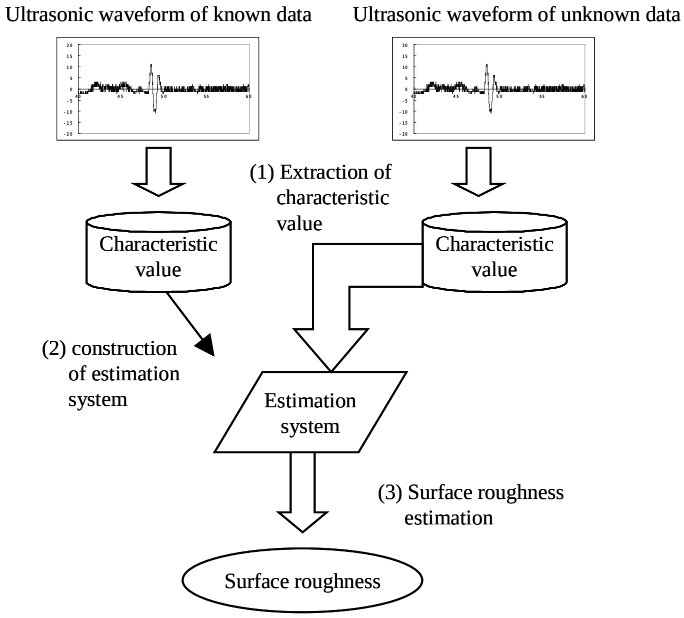

Fig. 4. Three stages of our method.

C. *The target and definition of roughness*

In our experiments, the target is a phantom made by mixture of gelatin and water. The phantom is standardized by Electronic Industries Association of Japan, and this is imitated as a soft tissue of a human. We made the phantoms with 5% gelatin, and this surface roughness is defined by a sandpaper. The smaller number of sandpaper is rougher. In this paper, we employ three kinds of surface roughness of the phantoms. A phantom filed by #60 sandpaper has the roughest surface. A phantom filed by #240 sandpaper has the second roughest surface. A phantom by no sandpaper has the smoothest surface. The phantom thickness is 13.0 mm.

III. SURFACE ROUGHNESS ESTIMATION BY FUZZY INFERENCE

In this method, the surface roughness is estimated with a fuzzy inference. The procedure of the estimation system is shown in Fig. 4. The estimation process of the surface roughness consists of three steps. First, the method extracts characteristic values from the echo data with known surface roughness. Second, the extracted characteristic values construct fuzzy membership functions. Third, we estimate the surface roughness of unknown data by using these membership functions.

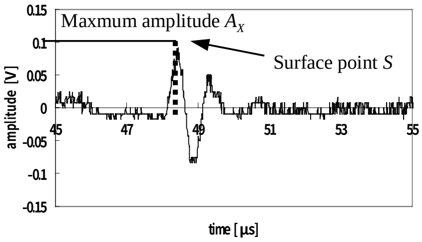

Fig.5. Example of echo data.

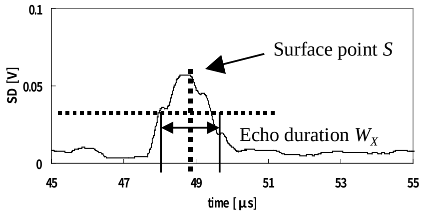

Fig.6. SD graph of amplitude of fig5.

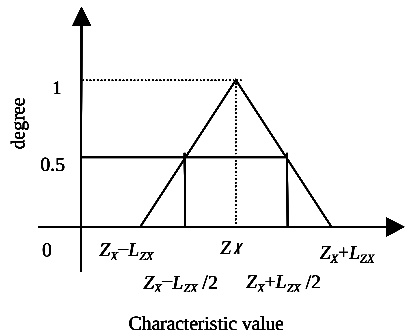

Fig. 7. Membership function.

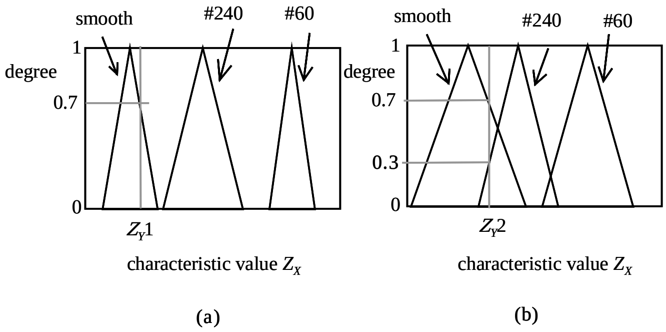

Fig. 8. Example of fuzzy function.

A. *Extraction of Characteristic Values*

We extract two characteristic values; the echo duration and the maximum amplitude value from the echo of the phantom surface.

Fig. 5 illustrates an example of the echo data. The maximum value of amplitude near the echo of phantom surface (this is known information as experimental parameter) is defined as the maximum amplitude A_X. Furthermore this point is defined as the surface point *S*. Fig. 6 illustrates standard deviation (SD) graph of amplitude in Fig. 5. SD is calculated using amplitudes of 1µs area at every sampling point of echo data. The echo duration is determined by these SD of the amplitude. 95 % of the SD value of point *S* is determined as threshold *TH*. The length of SD values being larger than *TH* in backward and forward of surface point is defined as the echo duration W_X. The characteristic value in the scanning area (height M mm and width N mm) is determined by the average of characteristic values of M×N points.

B. *Construction of Estimation System*

We employ fuzzy inference for construction of estimation system of surface roughness. We can derive knowledge from the characteristic of the echo. Generally, this knowledge can be expressed by a fuzzy if-then rule as follows,

IF Z_Y is Z_X, THEN *Y* is *X*,

where *Y* is the surface roughness of unknown data, Z_Y is characteristic value of unknown data, *X* (=*smooth* or *240* or *60*) is the surface roughness of known data, and Z_X is known characteristic value. This rule can be represented by fuzzy membership functions. The fuzzy membership function is defined as follows,

$$M_{Zx} = \begin{cases} 1-\dfrac{|x-Z_X|}{L_{Zx}} & (Z_X - L_{Zx} \le x \le Z_X + L_{Zx}) \\ 0 & (otherwise) \end{cases} \quad (1)$$

$$S(Z_Y) = \begin{cases} 1 & \text{if } x = Z_Y \\ 0 & \text{otherwise} \end{cases} \quad (2)$$

$$\mu_{Zx}(Z_Y) = \min(M_{Zx}, S(Z_Y)) \quad (3)$$

where M_{ZX} is membership function that is defined by equation (1), $S(x)$ is singleton function that is defined by equation (2), the $\mu_{ZX}(Z_Y)$ is the degree of the characteristic value Z_Y to Z_X, and Z_Y is the input characteristic value. Membership function M_{ZX} is a triangle shaped function, if $Z_Y = Z_X \pm L_{ZX}/2$, then $\mu_{ZX}(Z_Y) = 0.5$, and if $Z_Y = Z_X \pm L_{ZX}$, then $\mu_{ZX}(Z_Y) = 0$, as shown in Fig. 7. L_{ZX} is determined as SD values of each characteristic value. As shown by equation (3), by$\mu_{ZX}(Z_Y)$ is calculated as minimum of M_{ZX} and $S(Z_Y)$.

As shown in Fig. 8, membership functions are constructed

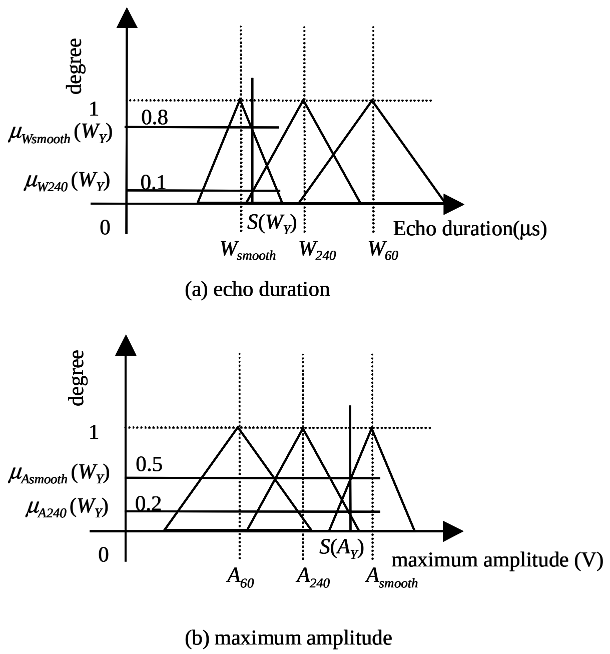

Fig. 9. Example of the process of the surface roughness estimation.

each surface roughness.

For example, in Fig. 8(a), case of input z_Y1, the degree of z_Y1 to z_{smooth} is 0.7; degrees to #240 and #60 are 0. Similarly, in Fig. 8(b), case of input z_Y2, the degree of z_Y2 to z_{smooth} is 0.7, the degree to #240 is 0.3 and degree to #60 is 0.

C. Surface Roughness Estimation

For two characteristic values, the fuzzy if-then rule for estimating surface roughness can be represented as follows,

$$\text{IF } (W_Y \text{ is } W_X) \text{ AND } (A_Y \text{ is } A_X), \quad \text{THEN } Y \text{ is } X.$$

where Y is the surface roughness of unknown data, W_Y is the echo duration of one of the characteristic value of unknown data, and A_Y is the maximum amplitude of another characteristic value of unknown data. X (=*smooth* or *240* or *60*) is the surface roughness of known data, W_X is the echo duration of known data, and A_X is the maximum amplitude of known data.

Y is calculated by given data $X = (W_X, A_X)$ as follows,

$$\mu_X(W_Y, A_Y) = \frac{\mu_{W_X}(W_Y) + \mu_{A_X}(A_Y)}{2} \qquad (4)$$

where $\mu_X(W_Y,A_Y)$ is a degree of unknown surface roughness Y to known surface roughness X, $\mu_{WX}(W_Y)$ is degree of unknown characteristic value W_Y to known characteristic value W_X, and $\mu_{AX}(A_Y)$ is degree of A_Y to A_X. The $\mu_{WX}(W_Y)$ and $\mu_{AX}(A_Y)$ are calculated by formula(1),(2) and (3). The $\mu_X(W_Y,A_Y)$ is calculated as arithmetic average of $\mu_{WX}(W_Y)$ and $\mu_{AX}(A_Y)$. The surface roughness X that has highest value of $\mu_X(W_Y,A_Y)$ is determined the surface roughness Y.

Fig.9 shows the example of the process of the surface roughness estimation. Firstly, characteristic values (W_Y, W_X) are extracted from unknown data whose surface roughness is Y. Extracted characteristic values are applied to fuzzy membership functions, and each degree of Y to X is calculated. In membership function of echo duration, $\mu_{Wsmooth}(W_Y)$ that is degree of W_Y to W_{smooth} is 0.8, $\mu_{W240}(W_Y)$ is 0.1 and $\mu_{W60}(W_Y)$ is 0. In membership function of maximum amplitude, $\mu_{Asmooth}(A_Y)$ that is degree of A_Y to A_{smooth} is 0.5, $\mu_{A240}(A_Y)$ is 0.2 and $\mu_{A60}(A_Y)$ is 0. Therefore, degree of Y to X is calculated by arithmetic average of each degree of each membership function. $\mu_{smooth}(W_Y, A_Y)$ that is degree of Y to *smooth* is calculated by equation (4), the result is 0.65, $\mu_{240}(W_Y, A_Y)$ is 0.15 and $\mu_{60}(W_Y, A_Y)$ is 0. In this case, since $\mu_{smooth}(W_Y, A_Y)$ is the highest value, Y is estimated *smooth*.

IV. Experimental Results

A. Preliminary experiment result

As a preliminary experiment, we have experimented using iron files to validate relationship between surface roughness and characteristic values. The roughness of iron file is standardized by Japanese Industrial Standard (JIS). A rough-cut file has the roughest surface. A second-cut file has the second roughest surface. A smooth-cut file has the smoothest surface. Thirty point data were acquired each surface roughness. Table I shows the average and ± standard deviation of each characteristic values of each surface roughness. The experimental result indicated that our characteristic values depend on surface roughness.

TABLE I
Characteristic Value of Each Surface Roughness
(Average of 30 points)

	Maximum Amplitude [V]	Echo Duration [μs]
Smooth-cut file	4.83±0.0	0.057±0.005
Second-cut file	4.76±0.048	0.064±0.011
Rough-cut file	3.37±0.253	0.092±0.012

TABLE II
Characteristic Value of Known Data
(Average of 800 points)

	Maximum Amplitude [V]	Echo Duration [μs]
smooth	0.107±0.011	0.214±0.006
#240	0.082±0.004	0.236±0.041
#60	0.067±0.014	0.458±0.224

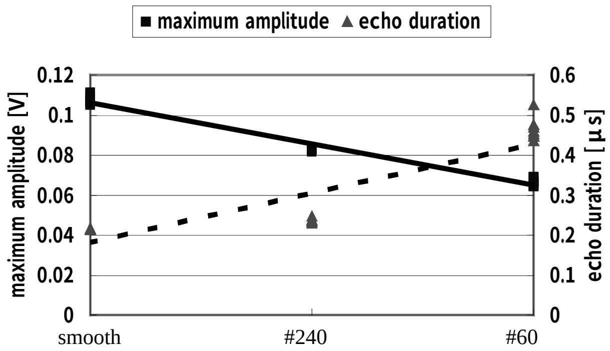

Fig.10. Approximated curve of characteristic value of known data.

TABLE III
CHARACTERISTIC VALUE OF UNKNOWN DATA
(AVERAGE OF 100 POINTS)

	Maximum Amplitude [V]	Echo Duration [μs]
smooth	0.112±0.003	0.205±0.003
#240	0.078±0.004	0.247±0.021
#60	0.058±0.011	0.489±0.112

TABLE Ⅳ
RESULT OF SURFACE ROUGHNESS ESTIMATING

	Estimated as smooth	Estimate as #240	Estimate as #60
smooth	<u>8/8</u>	0/8	0/8
#240	0/8	<u>8/8</u>	0/8
#60	0/8	0/8	<u>8/8</u>

B. Result of proposed method

The proposed method was applied to the phantoms with three kinds of surface roughness (smooth, #240, #60). Eight samples per a surface roughness were employed as known data (total 24 samples). Membership functions were constructed using characteristic values of these known 24 phantoms. Scan area was *x* direction 10 mm and *y* direction 10 mm. Total 100 points data per a sample were acquired. 800 point data were acquired each surface roughness. Table II shows the average and the standard deviation of each characteristic value of the known data at each surface roughness. Fig. 10 shows approximated curve of characteristic values of known data. As unknown data, we prepared eight phantoms per each surface roughness (smooth, #240, #60) and applied them to our estimation system. Scan area was *x* direction 10 mm and *y* direction 10 mm. Total 100 point data per one sample were acquired. Characteristic value of unknown data was determined by average of 100 points characteristic value. Table III shows the average and the standard deviation of each characteristic value of unknown data at each surface roughness. The results are tabulated in Table Ⅳ. From the result, the accuracy of our method was 100%(24/24). When known data and unknown data were replaced to perform cross-validation, the result successfully estimated all samples at 100%. Consequently, we could estimate the surface roughness of phantom by our fuzzy inference method.

V. CONCLUSION

In this paper, we have proposed the surface roughness estimating method from the ultrasonic waveform using fuzzy inference. In preliminary experiment, the result validated relationship between surface roughness and characteristic values. Our method can estimate the surface roughness of phantom automatically. By the experiment using the phantom, the accuracy of estimation of the surface roughness was 100%(24/24). This result has suggested the possibility of adaptation to human cartilage. It remains as future works to apply our method to other surface roughness and to human cartilage.

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