New Dynamic Fiber Orientation Sensor Based on Dielectric Anisotropy Measurement Technology

HIDETADA SAWAMOTO and SHINICHI NAGATA

Oji Paper Co., Ltd.
Advanced Technology Research Laboratory
4-3-1 Jokoji, Amagasaki, Hyogo 660-8577
Japan
hidetada-sawamoto@ojipaper.co.jp

ABSTRACT

A new fiber orientation sensor has been developed and tested on an actual paper machine to demonstrate its capability to function as a real-time monitoring system.

First, we demonstrate the ability of the sensor system to detect the change in the fiber orientation angle while the sensor head, and not the paper, was intentionally rotated from –90° to +70° with respect to the paper-traveling direction. Next, we demonstrate that this system can successfully detect the change in the magnitude and angle of fiber orientation in running paper when the direction of material flow on the wire was changed on the paper machine. The angle and magnitude of fiber orientation were independently confirmed by SST and MOA measurements.

Furthermore, we found that the system was capable of measuring the basis weight and the moisture content of running paper while detecting the angle and magnitude of fiber orientation.

INTRODUCTION

Fiber orientation is closely related to important physical properties represented, for example by the dimensional stability of paper, which is widely known for a decisive factor of paper curl phenomena.

Several offline methods for measuring the fiber orientation, for example, the water diffusion method [1], ultrasonic method [2], and microwave method [3] have been proposed and some of them are in practical use. The data presented by these methods have been utilized to improve paper quality as well as paper making processes. However, all of these methods are for offline measurement of only a tiny part of the paper roll. That tiny part may not represent the characteristic of the entire roll. In addition to this, the measurement is carried out after the completion of paper making. Even if you find the measured values deviate from the specifications, you have no choice but to send the roll to the pulper.

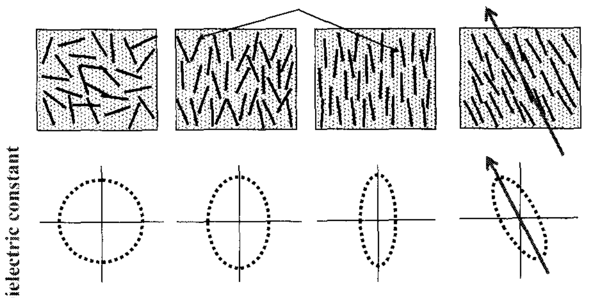
Our new online dynamic fiber orientation sensor, which is based on dielectric anisotropy measurement technology, can measure not only the average fiber orientation angle and its magnitude but also the fluctuation of these properties while paper is running on the paper machine. This system measures these data with every 1.5 second interval.

We have already reported the basics of this new dynamic fiber orientation sensor using the microwave method [4]. In this paper, we report the current situation of the development, where the sensor system has been installed in an actual paper machine, and its performance has been examined.

PRINCIPLE

Fiber orientation and dielectric anisotropy

Since a paper sheet is very thin, we consider it is reasonable to assume that paper is a plane. Fig. 1 shows the model that represents the relationship between fiber orientation and dielectric anisotropy. If the fiber orientation of the paper sheet is isotropic (further left), the dielectric plot becomes an approximate circle. If the fiber orientation is anisotropic, the dielectric plot is an ellipse. The major axis of the ellipse indicates the direction of fiber orientation (further right in Fig.1). The fiber orientation magnitude is represented by the degree of the deformation from the circle (in practice it is represented by the difference between the lengths of the major and minor axes.)



Isotropic | Slightly Anisotropic | Strongly Anisotropic | Strongly Anisotropic

Figure 1 Fiber orientation and dielectric anisotropy

Dielectric resonator and resonance curve shift

Fig. 2 shows one of the five sensors utilized in our system (see Figure 4 as well). It consists of rectangular dielectric resonator, rod antennas, and shield case. We take advantage of the electric fields of the evanescent waves to measure the direction and its intensity of fiber orientation.

In order to achieve these, the evanescent wave was designed to emit in such a way that it orients itself to be parallel to the long side of the dielectric resonator. When a paper sheet is placed on the top of the dielectric resonator, the resonance curve shifts toward the lower frequency with the lower intensity, as shown in Fig.3. The frequency shift (f_0-f_s) is proportional to the product of the dielectric constant and the sample thickness. Since it is reasonable to assume the paper thickness is constant for paper manufacturing process, "f_0-f_s" should be proportional to the dielectric constant. The sample that possesses dielectric anisotropy should show the highest dielectric constant value when the direction of fiber orientation matches to the direction of the above mentioned evanescent wave. Therefore, to determine the direction of the fiber orientation, one has to rotate either the sample (here, paper) or the sensor head and find the direction where the maximum dielectric constant is observed.

To avoid this complexity and determine fiber orientation angle and magnitude simultaneously by a "one-shot" measurement, we designed an innovative system where five sensors were employed. The detail of the design will be explained in the following section.

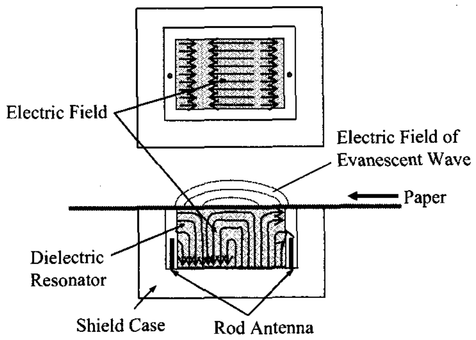


Figure 2 Sensor part of this system

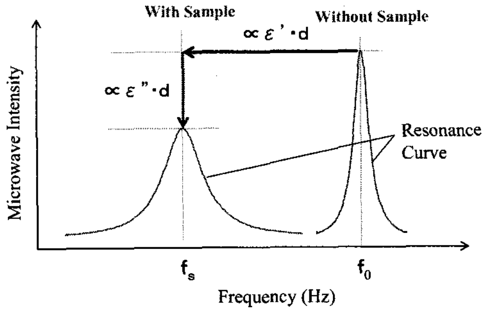


Figure 3 Relationship between resonance curve and dielectric constant

Layout of dielectric resonator and orientation pattern

As shown in Fig. 4, the five dielectric resonators are placed at every 72°. By plotting the frequency shifts of the five resonators on polar coordinates, the orientation pattern shown in Fig. 4 is obtained. The major axis of the orientation pattern indicates the direction of the fiber orientation angle. The fiber orientation magnitude is represented by the difference between the lengths of the major and minor axes of the orientation pattern.

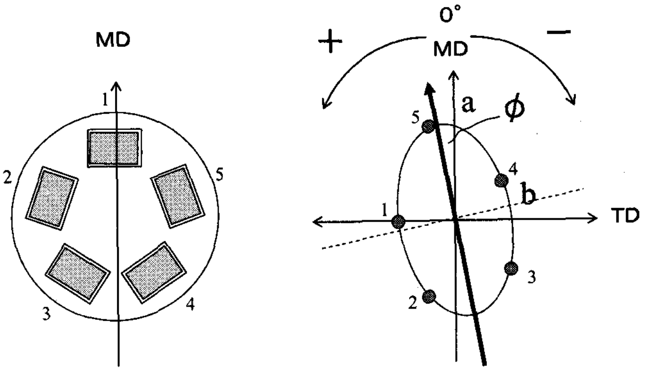


Figure 4 Layout of dielectric resonators and orientation pattern

Measurement of basis weight

We found that our system is capable of measuring the basis weight and moisture content of paper while measuring fiber orientation angle and its magnitude.

The basis weight can be calculated by the following procedure. By applying the perturbation theory to a dielectric resonator, the relationship between the dielectric constant and the frequency shift is expressed as follows [5]:

$$(\omega_s - \omega_s)/\omega_0 = \int_{\Delta v}[(P + J/j\omega_a)E_a^* + \mu_0 MH_a^*]\,dv/4W \qquad (1)$$

$$W = \int_v \varepsilon_s |E_a|^2 dv \qquad (2)$$

$$\omega = 2\pi f \qquad (3)$$

Here, ω_s and ω_0 are the angular frequencies with and without a sample, respectively. P, J, E_a, and M are the electric polarization, conductive current density, electric field, and magnetic field, respectively. ε_s and f are the dielectric constant of the resonator and the frequency. The reference symbol "*" represents a complex number. The term "$\mu_0 M H_a^*$" is equal to zero because paper is nonmagnetic. Therefore, Eq. 1 is converted to Eq. 4.

$$(\omega_s - \omega_s)/\omega_0 = \int_{\Delta v}[(P + J/j\omega_a)E_a^*]\,dv/4W \qquad (4)$$

Next, we divide the right-hand side of Eq. 4 into real and imaginary parts. The real part is expressed as follows:

$$(\omega_s \ \omega_s)/\omega_0 = -\int_{\Delta v} \varepsilon_0(\varepsilon' - 1)E_a^2 dv/4W \qquad (5)$$

By integrating the integral part on the right-hand side in Eq. 5, we obtain Eq. 6.

$$(\omega_s - \omega_s)/\omega_0 = -\varepsilon_0(\varepsilon' - 1)E_a^2\Delta V/4W \qquad (6)$$

Because ΔV is the volume of the sample, it is equal to the product of the measurement area "S" and the sample thickness "d." When these values are substituted in Eq. 6, we obtain Eq. 7.

$$(\omega_s - \omega_s)/\omega_0 = -\varepsilon_0(\varepsilon' - 1)E_a^2 Sd/4W \qquad (7)$$

The sample thickness is expressed as follows:

$$d = b/e \qquad (8)$$

Here, b is the basis weight of paper, and e is the density of paper. Therefore, Eq. 7 is converted into Eq. 9 as follows:

$$(\omega_s - \omega_s)/\omega_0 = -\varepsilon_0(\varepsilon' - 1)E_a^2 Sb/4We \qquad (9)$$

When Eq. 3 is substituted in Eq. 9, we obtain the following equation:

$$f_0 - f_s = \varepsilon_0(\varepsilon' - 1)E_a^2 Sb/4We \qquad (10)$$

The stored energy "W" is a constant determined by two constants— ε_s and E_a. ε_0 and ε' are constants determined by the instrument and the sample, respectively. If d is assumed to be constant, Eq. 10 can be represented as follows:

$$\Delta f = Ab \qquad (11)$$

Here, Δf is the difference between the resonance frequency with and without the sample, and A is a constant. In other words, the basis weight is directly proportional to Δf. If constant A is known, we can calculate the basis weight by measuring Δf.

Measurement of moisture content

As shown in Fig. 3, the microwave intensity shift is proportional to the product of the dielectric loss and the thickness of the sample. If we assume that the sample thickness is constant, the microwave intensity shift changes depending on only the dielectric loss of the sample. One substance that has a large dielectric loss is water. Consequently, the microwave intensity shift is strongly affected by the moisture content. By plotting an analytical curve of the microwave intensity shift versus the moisture content, we can determine the moisture content by measuring the microwave intensity shift.

EXPERIMENT

Equipment configuration

As shown in Fig. 5, our system is configured by the sensor head, which comprises five dielectric resonators, a microwave sweeper, a controller that rapidly calculates the five resonance frequencies, and a personal computer that calculates the angle and magnitude of fiber orientation from the five resonance frequencies. The results of the fiber orientation are instantly monitored on the personal computer display.

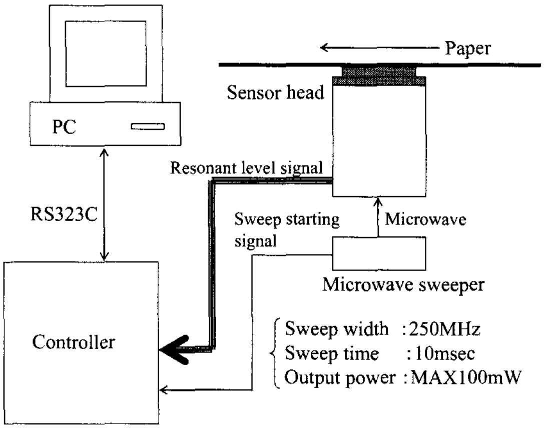


Figure 5 Equipment configuration

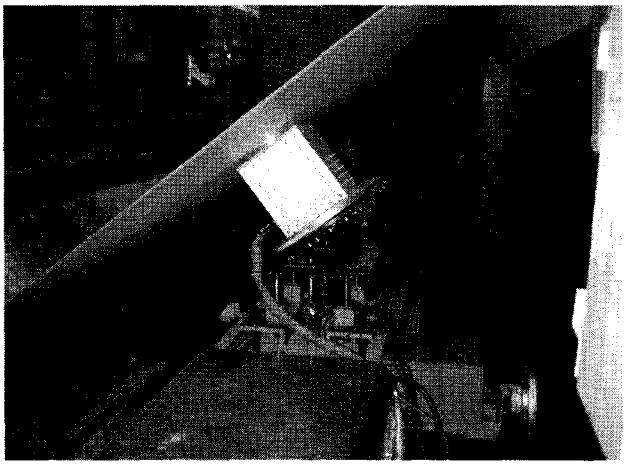


Figure 6 Sensor head set on actual paper machine in our mill

Setting on actual paper machine

Fig. 6 is the photograph of the sensor head installed in an actual paper machine. The sensor head was positioned 40 or 60 cm from the edge of the driving side of the paper machine. In the standby mode, the sensor head is shifted to a lower position, and it does not maintain contact with the paper sheet. The sensor head is shifted to the upper position only in the measurement mode where it makes contact with the paper sheet. If the paper sheet is suddenly cut due to an unexpected problem, the sensor head is automatically shifted to a lower potion by detecting the paper-cutting signal. When the paper machine is restored, the sensor head is shifted back to the upper position by operating a switch.

Verification of fiber orientation

We performed two experiments to verify the fiber orientation angle. In one experiment, the sensor head was intentionally rotated from –90° to 70°, at intervals of 10°, with respect to the paper-traveling direction. In the other experiment, the direction of material flow on the wire was intentionally changed on the actual machine. The measured magnitude and angle of fiber orientation were independently confirmed by two conventional offline measurement instruments—Sonic Sheet Tester and Microwave Molecular Orientation Analyzer.

Verification of basis weight

Online measurement was carried out by using four samples with different basis weights and identical dielectric constants. Then, the relationship between ⊿f and the basis weight, which was obtained by gravimetry, was examined.

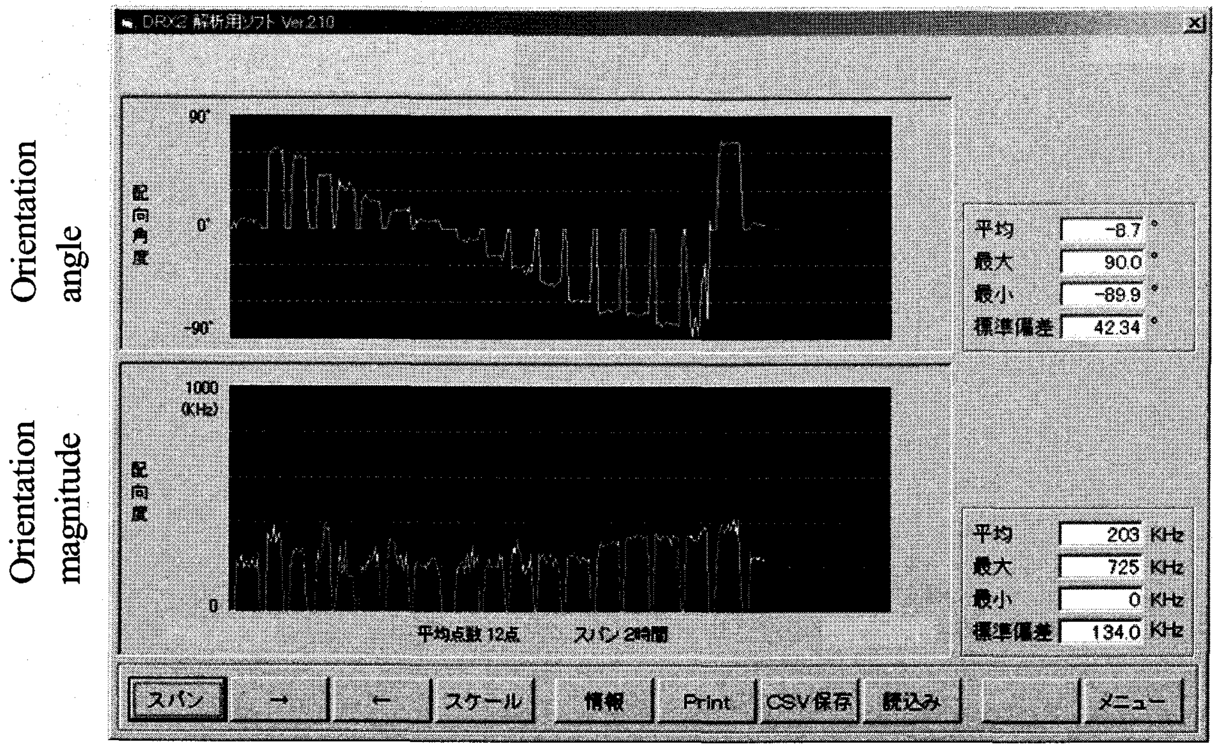
RESULTS AND DISCUSSION

Fig. 7 shows a screenshot of the data for the experiment in which the sensor head was intentionally rotated from –90° to 70° at intervals of 10° to the paper-traveling direction. In this figure, the horizontal axis represents the time. In this experiment, we changed the rotating angle of the sensor head at intervals of a few minutes. The vertical axis of the upper plot represents the fiber orientation angle. If the fiber orientation angle is 0°, it implies that the fiber orientation is parallel to the paper-traveling direction. The measured values of the fiber orientation angle vary at intervals of around 10°. The vertical axis in the lower plot represents the fiber orientation magnitude. Fig. 8 shows the relationship between the sensor head rotation angle and the measured fiber orientation angle. The dotted line indicates the theoretical value when the fiber orientation angle is 0°. As shown in Fig. 8, the plot of sensor head rotation angle against the measured angle is in good agreement with the theoretical value. This implies that the measured angle correctly follows the rotation of the sensor head and the measurement range of the fiber orientation in this system is very wide. Therefore, this system can be applied to polymer films, for example, PET, with large molecular orientation angles.

Fig. 9 shows the result for the experiment in which the direction of material flow on the wire was intentionally changed on the actual machine. In part A, the machine was operated under normal condition, i.e., before changing the material flow direction. The fiber orientation angle was about 0°. When the direction of material flow was changed in Part B, the fiber orientation angle shifted toward the negative region. Table 1 shows the comparison between two conventional offline measurement instruments—SST (Sonic Sheet Tester) and MOA (Microwave Molecular Orientation Analyzer). The data from our system strongly correlated with the readings of these offline instruments. Our system was

Table 1 Comparison between two offline instruments

	Before Changing	After Changing
Our System	1 degree	-10 degree
MOA	2 degree	-7 degree
SST	1.8 degree	-2.3 degree



平均 -8.7 °
最大 90.0 °
最小 -89.9 °
標準偏差 42.34 °

平均 203 KHz
最大 725 KHz
最小 0 KHz
標準偏差 134.0 KHz

Figure 7 Screenshot of data for the case where the sensor head was rotated from 70° to –90°

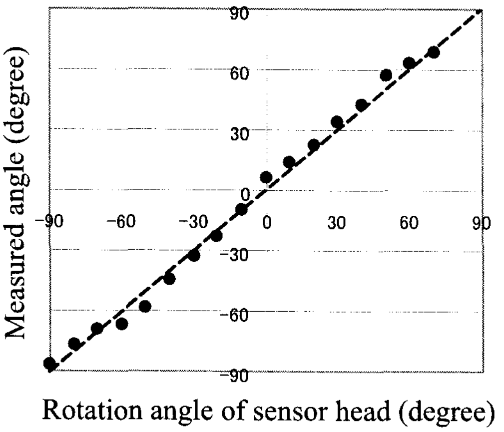


Figure 8 Rotation angle of sensor head versus measured angle

able to detect the changes in the fiber orientation successfully. The result of continuous measurement for around 50 h is shown in Fig. 10. The stability of continuous measurement was confirmed.

Fig. 11 shows the relationship between the basis weight of paper and measured ⊿f. The measurement of ⊿f was carried out by using four samples with different basis weights. After completion of the paper-making process, the basis weight of the paper sample was measured offline. The basis weight was proportional to ⊿f and the two parameters exhibited a linear correlation. The slope of the line is A in Eq. 11.

Fig. 12 shows an example of dynamic measurement. On the computer screen, four plots are visible—orientation angle, orientation magnitude, basis weight, and moisture content. Their measured values are instantly calculated and updated at intervals of 1.5 s.

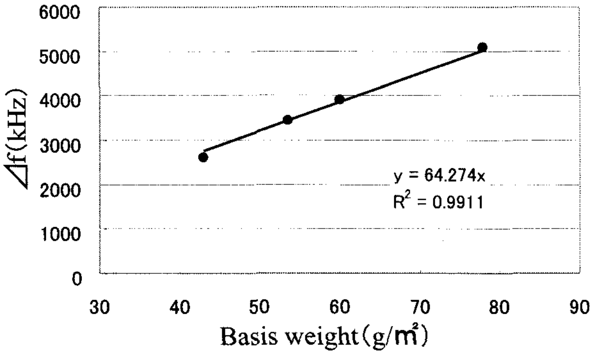
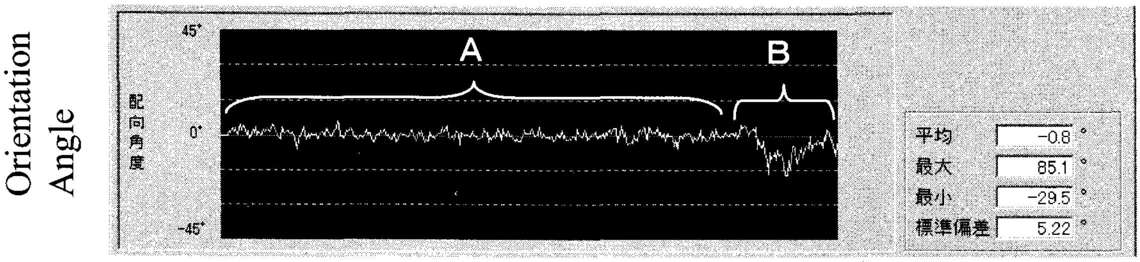


Figure 11 Relationship between basis weight and ⊿

CONCLUSION

We have developed a new dynamic fiber orientation sensor that employs the microwave method. The accuracy of the orientation angle was evaluated by this method. Furthermore, in our system, the basis weight was proportional to ⊿f; therefore, the basis weight could be calculated by measuring ⊿f. The principal



平均 -0.8 °
最大 85.1 °
最小 -29.5 °
標準偏差 5.22 °

A: Before changing B: After changing

Figure 9 Measured fiber orientation angle before and after changing condition

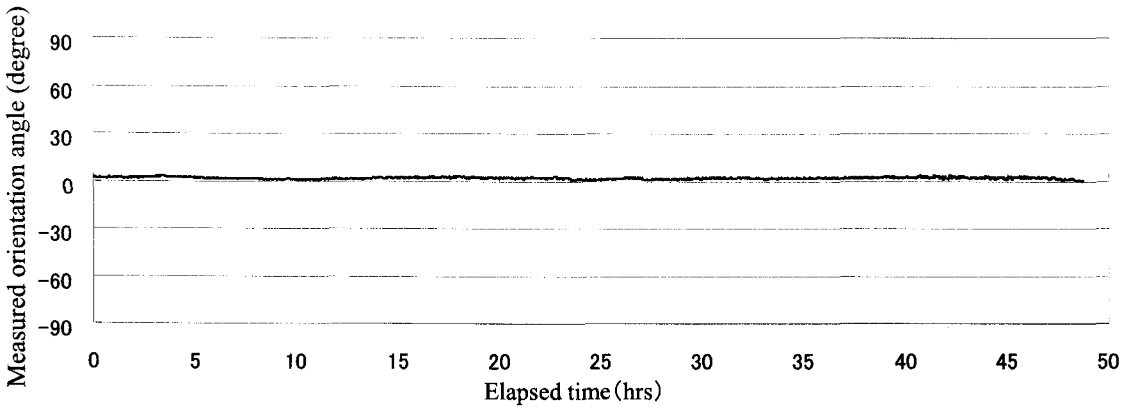


Figure 10 Data from continuous measurement for around 50 h

characteristics of our system are as follows:

1. It can measure the magnitude and angle of fiber orientation across the entire thickness of the paper.
2. It can be applied to polymer films such as a stretched PET film.
3. It can measure the basis weight and moisture content.

ACKNOWLEDGEMENT

The author wishes to thank Dr. Fumiaki Okada of honorary professor of National Defense Academy for teaching and help to develop this sensor system. The data showed a strong correlation with that obtained from two conventional offline measuring instruments—SST and MOA.

REFERENCE

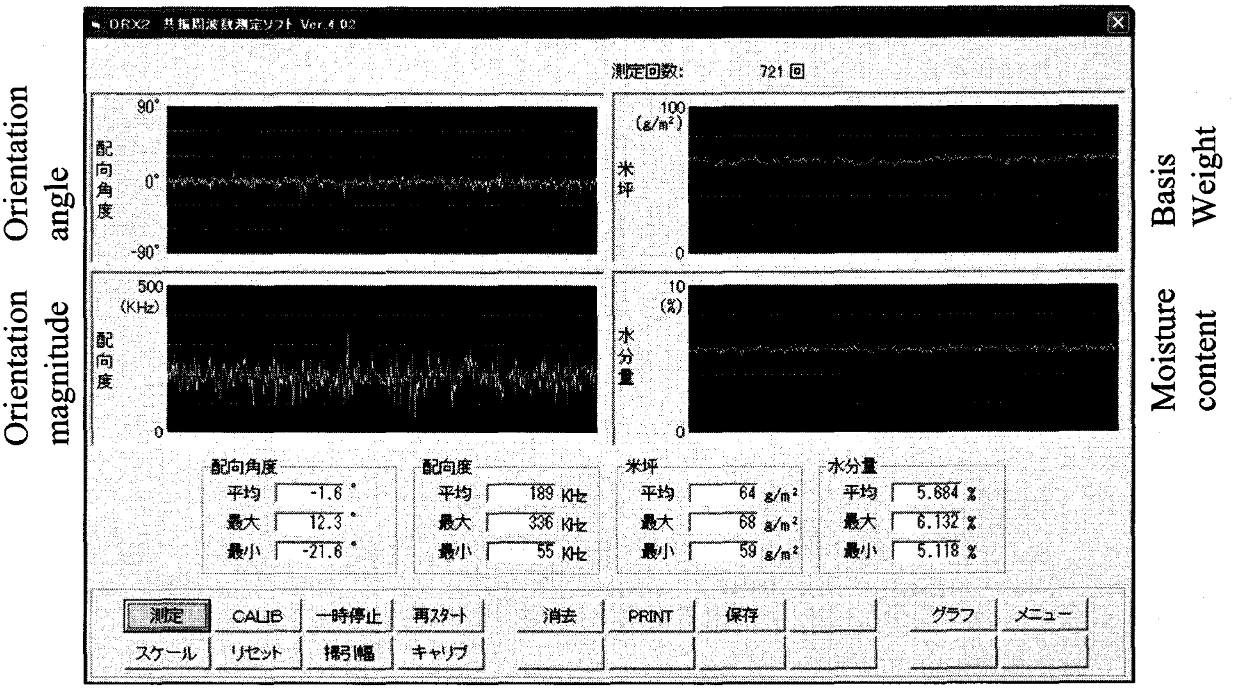
1. Kato, Y., Kuriyama, T. and Nagata, M., Jp Patent Application No. S61-142464

2. Craver, J.K. and Taylor, D.L., Tappi, 48(3):142(1965)

3. Nagata, S. and Koyama, K., Seikei-kakou, 11(2):142(1999)

4. Nagata, S., Proceedings of Pan Pacific Conference, 158-168(2002)

5. Fujisawa, K. and Okamoto, N., Maikurohakairoreidaienshu, Corona Publishing, 156-157(1978)



測定回数: 721 回

	配向角度	配向度	米坪	水分量
平均	-1.6 °	189 KHz	64 g/m²	5.684 %
最大	12.3 °	336 KHz	68 g/m²	6.132 %
最小	-21.6 °	55 KHz	59 g/m²	5.118 %

Figure 12 Example of dynamic measurement of fiber orientation angle, magnitude, basis weight, and moisture content