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Development of a New On-line Fiber Orientation Sensor Based on Dielectric Anisotropy

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ABSTRACT

A new method is proposed for the on-line measurement of the fiber orientation of sheet materials. The measurement of fiber orientation is very important in manufacturing paper sheets, non-woven fabrics, and glass sheets, because fiber orientation strongly affects product properties represented by, for example, dimensional stability of paper.

A method developed in this research utilizes anisotropy of dielectric constants of sheet materials as a key characteristic to determine the fiber orientation. The new on-line sensor, consisting of 5 microwave dielectric resonators set in different directions, was designed to detect the fiber orientation while paper is running with high speed on a paper machine. This sensor can determine the direction and the degree of fiber orientation from the measured direction of the maximal dielectric constant and its variation, respectively.

The fundamental performance of this system was examined by the static measurement of printing grade paper, which gave a satisfactory result. Then, the dynamic measurements were done at a speed of 1,000 m/min by using a high-speed test-coating machine.

Keywords: Fiber Orientation, Anisotropy, Dielectric Constant, On-line Sensor, Dielectric Resonator.

1. INTRODUCTION

Molecular orientation is one of the most important information indispensable for the characterization of polymer materials. The molecular orientation is closely related to the anisotropy of the mechanical, thermal, optical, electromagnetic and physicochemical properties of polymers [1]. For example, the molecular orientation of the center part in the transverse direction of the biaxially stretched films like PET film is nearly isotropic and the anisotropy gradually grows stronger as the measured point approaches the edges of the films. This phenomenon, which is called "bowing phenomenon" is an essential and unavoidable problem in the biaxially stretching process [2].

A similar phenomenon is found in paper sheets, which consist of polymer materials like cellulose. In the paper making process, it is very important to unify the fiber orientation at every point of the transverse direction [3]. Actually, it is difficult to do that because the fiber orientation is changeable near the edges of the paper sheets. It may be natural rather than extraordinary that the long and slender ones like molecular chains or pulp fibers are oriented to one direction by some force like shear stress while they change into

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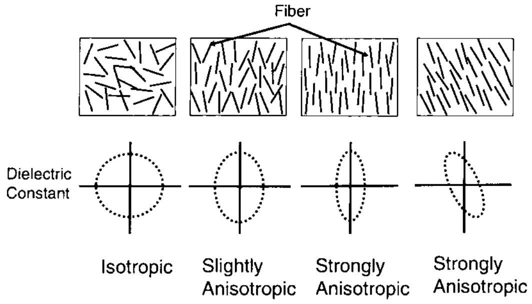


Fig . 1. Relation between fiber orientation and dielectric anisotropy.

the solid state from the fluid state. To keep the fiber orientation uniform is our mission as well as our subject.

There are few instruments for the on-line measurement of the fiber orientation at present. Though a method, which utilizes the reflection of the light from the surface of the paper sheet, was developed, it measures only the surface' s fiber orientation [4] . For the laboratory use, the ultra-sonic velocity method is well used. This method, which measures the anisotropy of the modulus of elasticity, is strongly influenced by the anisotropy caused by restriction in the drying process of paper sheets [5] . As a result, the orientation angle deviates from the actual one.

On the other hand, it is said that "Microwave Molecular Orientation Analyzer" (MOA) with a microwave cavity resonator [6] shows the actual orientation angle [5] . It can evaluate the fiber orientation from the anisotropy of dielectric constant. By utilizing the difference between the ultrasonic velocity method and MOA, the study that predicts the direction of the restriction in the drying process has also been done [5] .

Based on the technology of MOA, we developed a new method for the on-line measurement of the fiber orientation by employing the microwave dielectric resonators. And we succeeded in the measurement of the fiber orientation of the base paper at a speed of 1,000 m/min by using our high-speed test-coating machine.

2. PRINCIPLE

2.1 Dielectric Anisotropy and Fiber Orientation

Fig.1 shows the relationship between the fiber orientation and the anisotropy of dielectric constant. If the paper sheet is isotropic, the pattern plotted by dielectric constants on the polar coordinates shows a circle. If the paper sheet has anisotropy, the pattern shows an ellipse. The direction where the dielectric constant has a maximum shows the orientation angle. The difference in the dielectric constant between the maximal and minimal directions is a measure of the degree of fiber orientation. Our new method as well as "MOA" is based on the anisotropy of dielectric constant.

In the polymer film' s makers, the molecular orientation of the polymer films is usually measured by birefringence, which is defined as the difference between the maximal refractive index "n" and the minimal one. Dielectric constant "ε' " is equal to the square of refractive index "n" in the high frequency range such as visible light region because both "ε' " and "n" are caused by electron polarization. From the above fact, it is reasonable to measure the molecular orientation of the polymer films or paper sheets by using the anisotropy of dielectric constant instead of refractive index.

Anisotropy of dielectric constant is caused by two main factors as shown in Fig.2. One is electron polarization and the other is the shape of the islands in the islands-sea structure.

In the former case, electron clouds of the molecular chains in the polymer materials are attracted to the positive of the electric field when the electric field is applied. Electron polarization, which is the origin of dielectric constant and refractive index, is caused by this distortion of the electron clouds. The anisotropy of this electron polarization appears in the polymer because molecules are connected with each other as a molecular chain. As a result, dielectric constant has a maximum in the direction parallel to the molecular chain and has a minimum in the direction perpendicular to the molecular chain in general.

In the latter case, the shape of the islands in the

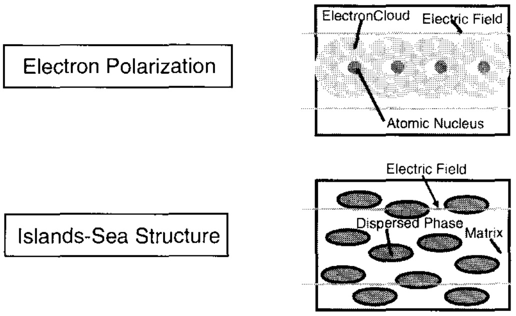


Fig. 2. Two factors which cause the anisotropy of dielectric constant.

islands-sea structure causes the anisotropy of dielectric constant. Fig. 3 illustrates the angular dependence of dielectric constant based on the shape of the islands. If the shape of the islands is elliptic and each island is arranged in parallel, macroscopic dielectric constant has a maximum in the direction of major axis of ellipse even if both matrix and dispersed phase are dielectrically isotropic by themselves. Maximal dielectric constant εa can be expressed by Eq. (1), which is derived from the electromagnetic theory. Minimal dielectric constant εb is given as Eq. (2) by the same way.

$$\varepsilon_a = \varepsilon_m [(\varepsilon_f - \varepsilon_m) \{V_f + (1 - V_f) A_a\} + \varepsilon_m] / \{ (\varepsilon_f - \varepsilon_m) (1 - V_f) A_a + \varepsilon_m \} \tag{1}$$

$$\varepsilon_b = \varepsilon_m [(\varepsilon_f - \varepsilon_m) \{V_f + (1 - V_f) A_b\} + \varepsilon_m] / \{ (\varepsilon_f - \varepsilon_m) (1 - V_f) A_b + \varepsilon_m \} \tag{2}$$

Here, ε_m and ε_f are the dielectric constants of matrix and dispersed phase respectively. Vf is the volume fraction. A_a and A_b are parameters shown as Eq. (3) and Eq. (4) respectively. The parameter of "e" is the eccentricity of ellipse shown as Eq. (5).

$$A_a = \{ (e^{2\ 1}) / 2e^2 \} [2 + (1/e) \ln \{ (1-e) / (1+e) \}] \tag{3}$$

$$A_b = (1/2e^2) \{1 + \{ (1-e^2) / 2e\} \ln \{ (1-e) / (1+e) \} \} \tag{4}$$

$$e = (1 - (b/a)^2)^{1\ 2} \tag{5}$$

From above equations, it can be numerically explained that the longer and slenderer elliptic shape becomes, the more dielectric anisotropy grows [7].

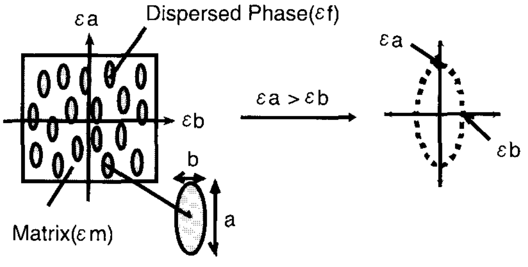


Fig. 3. Dielectric constants ε a and ε b can be show by εm, εf, , and vfin island-sea structure.

In the case of paper, both the electron polarization and the shape of islands in the islands-sea structure give the anisotropy of dielectric constant to the paper. In other words, dielectric anisotropy of the cellulose itself is derived from the electron polarization of its molecular chain and the shape of the fibers as island gives the dielectric anisotropy supposing that the paper has an islands-sea structure. As a result, both of them cause the dielectric anisotropy of the paper sheets. It can be predicted that this method is high sensitive to measure the fiber orientation of paper sheets in principle because both of them give a maximum of the dielectric constant in the fiber' s direction.

2.2 Dielectric Resonator

Rectangular microwave dielectric resonator shown in Fig. 4 has been employed to measure the anisotropy of dielectric constant of paper sheets. One rod antenna excites the dielectric resonator and the other antenna detects the strength of the electric field of the resonator. Evanescent waves exude from the surface of the dielectric resonator though almost all the resonant energy is confined inside the dielectric resonator. Paper sheets pass through the evanescent waves touching the surface of the dielectric resonator. It is important that the electric fields of the evanescent waves are parallel to the long side of the dielectric resonator as shown in Fig. 5. If the electric fields were not parallel but circle, dielectric anisotropy couldn' t be measured. The resonance curve shown in Fig. 6 is obtained

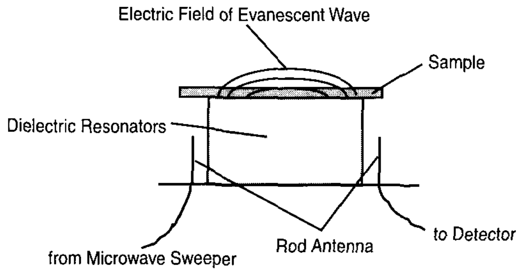


Fig. 4. Rectangular Dielectric Resonator.

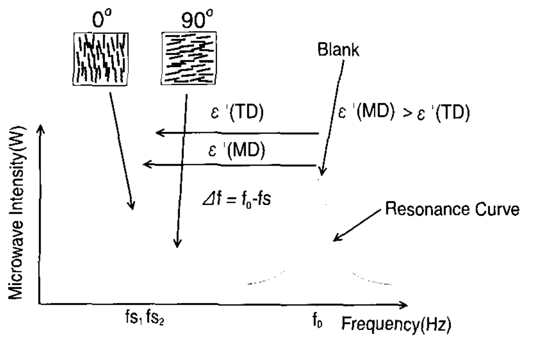


Fig. 6. Relation between resonance curve and dielectric constant.

if the frequency is sweeped. When a sample is put on the dielectric resonator, the resonant frequency shifts to the lower frequency in proportion to the dielectric constant in the direction of the electric field of the evanescent wave.

Therefore, if the angular dependence of the frequency shift, which is defined as the difference between with and without the sample, is measured during full rotation of the dielectric resonator or the sample, the anisotropy of dielectric constant can be obtained. The direction of the maximal frequency shift corresponds to the direction of the maximal dielectric constant. This direction reflects the averaged direction of the fiber orientation. In this way the fiber orientation of paper sheets can be obtained quite easily by rotating the paper sheet around the normal to the sheet plane. But the rotation of the sample or the dielectric resonator is not suitable for the on-line estimation of the fiber orientation in the rapid production process of the paper sheets.

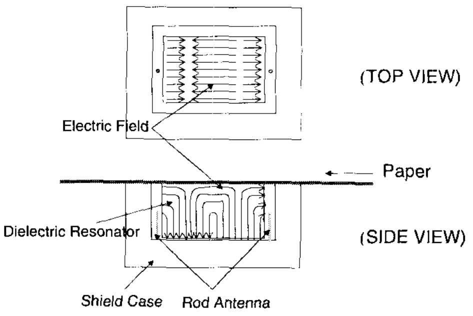


Fig. 5. Distribution of electric field in dielectric resonator.

2.3 Arrangement of Dielectric Resonators

To solve this problem, we have gotten the following new idea successfully. As shown in Fig. 7, five dielectric resonators are prepared. Each resonator is set at every 72°. By plotting the frequency shifts of five dielectric resonators on the polar coordinates, the orientation pattern shown in Fig. 7 can be obtained repeatedly for every 1.5 second. The direction of the long axis of the orientation pattern corresponds to the averaged orientation direction of the fibers in the paper sheet. The degree of orientation is expressed by (a-b)/b, where a denotes the length of the long axis of the orientation pattern and b that of the short axis.

3. VERIFICATION OF FUNDAMENTAL PERFORMANCE

3.1 Sensitivity of Anisotropy

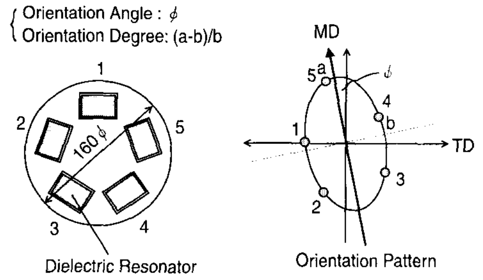


Fig. 7. Layout of dielectric resonators and orientation pattern.

In order to check the sensitivity of the dielectric resonator, biaxially stretched poly(ethylene terephthalate) film(PET film) was prepared, which had the thickness of 188μm and the orientation angle of +47° as evaluated by MOA. A sheet of PET film of 166mm φ diameter was cut of this film and put on the sensor head shown in Fig. 8. The resonant frequency was measured for the PET film set to different directions every 15°. The measured results for No.1 dielectric resonator are shown in Fig. 8. It is found that the resonant frequency has a maximum at the rotational angle of 47°, where the molecular chains are perpendicular to the electric field, and it has a minimum at the rotational angle of 137°, where the molecular chains are parallel to the electric field. The difference between the maximal frequency and the minimal frequency shows the sensitivity of this dielectric resonator. The difference, which is about 230KHz, is enough for the measurement because the standard deviation of the resonant frequency, which shows the stability of detecting the resonant frequency in this system, is less than 3~4KHz.

3.2 Comparison with MOA

In order to check the static and total accuracy of this system, printer paper on the market, the thickness of which was 92μm and the orientation angle of which was -7°, was put on the sensor head consisting of five dielectric resonators. The orientation angle measured by this system was -6.7°, which was nearly equal to the angle -7° measured by MOA. The orientation pattern measured by this system might be affected more or less by the nonuniformity intrinsic to the sensor head. In order to check this uniformity, which should give the same results for the different settings of the sample paper, the sample paper set on the sensor head was rotated by every 30° and the orientation pattern was recorded. The orientation angle evaluated from this pattern was plotted against the rotation angle of the paper, as shown in Fig. 9. The evaluated orientation angle is changed in parallel to the rotation angle of the paper, indicating the almost perfect uniformity of the system.

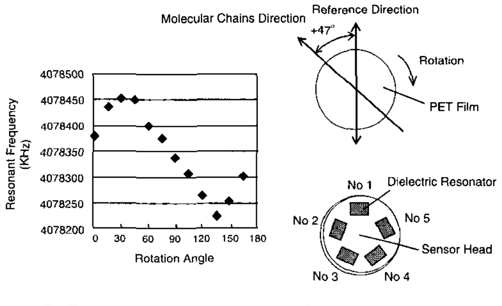


Fig. 8. Resonant frequency of No.1 dielectric resonator plotted against the rotation angle of PET film with an orientation angle of 47°

4. EXPERIMENT

4.1 Experiment on Our High-Speed Test-Coating Machine

The dynamic measurements of our system were proved at speeds of 50 m/min, 300 m/min, 600m/min and 1,000m/min by using our high-speed test-coating machine. Three kinds of base paper, the orientation degree of which were big, medium and small, were prepared. The basis weights of them were 40g/m^2, 40g/m2 and 60 g/m^2 respectively. A glass paper sheet, the basis weight of which was 20g/m^2, was also prepared. Fig. 10 shows the picture of the sensor head with five dielectric resonators. Fig. 11 shows the picture of the experimental system on our high-speed test-coating machine while the sample paper was run-

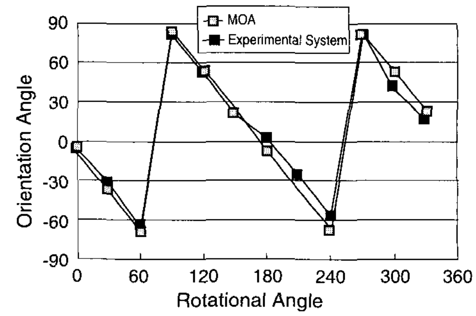


Fig. 9. Orientation angle of printer paper plotted against rotational angle.

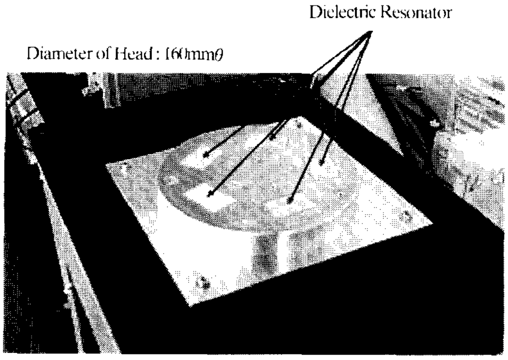


Fig. 10. Picture of the sensor head.

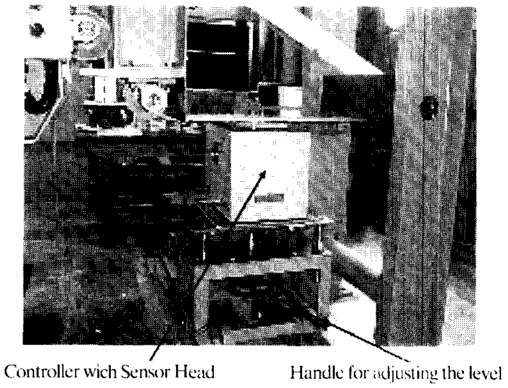


Fig. 11. Controller with sensor head on high-speed test-coating machine.

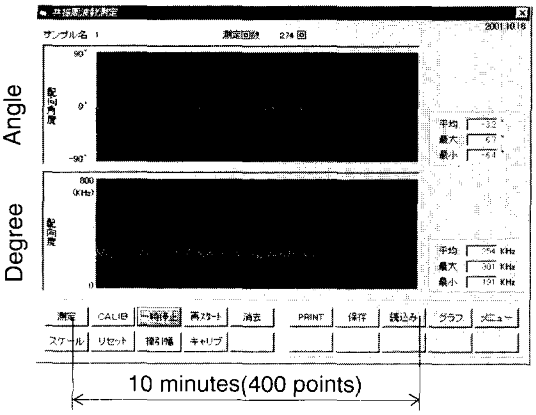
ning at a speed of 1,000m/min.

The controller with the sensor head was installed on the stand as shown in Fig. 11. The level of the sensor head was adjustable by using the handle. The paper was very steady as if the paper were stopping, flat without wrinkles and was contacted with the sensor head uniformly. The very stable results could be obtained. Fig. 12 shows the obtained orientation pattern and Fig. 13 shows the change of the orientation angle and the orientation degree against the measuring time. The results of three kinds of paper and a glass paper measured by the experimental system well agreed with those obtained by MOA.

This method doesn' t need to contact the paper to the sensor head in principle because of using the evanescent wave. But the sensor head was contacted with the paper sheets in order to stop the fluttering of the paper sheet.

4.2 Test on Manufacturing Machine

After succeeding in the experiment using our high-speed test-coating machine, we installed the sensor system on a real manufacturing machine in our mill to test the practicability of this system. The picture of the sensor head is shown in Fig. 14. The test results



サンプル名 1

測定回数 274 回

平均 -32 °

最大 67 °

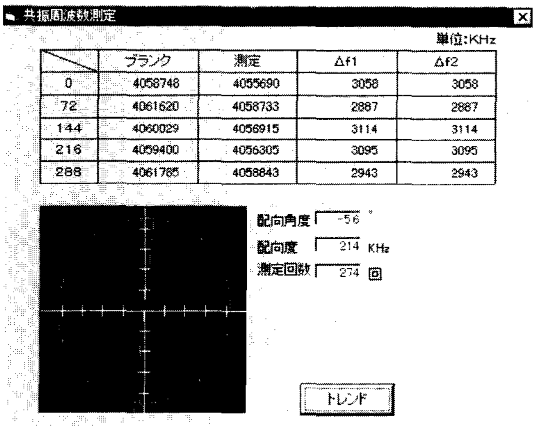
最小 -54 °

平均 254 KHz

最大 301 KHz

最小 191 KHz

Fig. 12. Orientation pattern of fine paper with a basis weight of 40g/㎡.



単位:KHz

	ブランク	測定	Δf1	Δf2
0	4058748	4055690	3058	3058
72	4061620	4058733	2887	2887
144	4060029	4056915	3114	3114
216	4059400	4056305	3095	3095
288	4061785	4058843	2943	2943

配向角度 -56 °

配向度 214 KHz

測定回数 274 回

Fig. 13. Change of orientation angle and orientation degree of the fine paper with a basis weight of 40g/㎡ against the measuring time.

will be reported in detail at the conference.

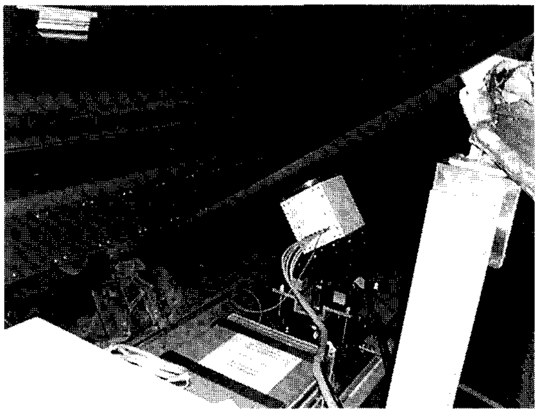


Fig. 14 . Sensor head on a manufacturing machine in our mill.

5. CONCLUSION

We have developed a new sensor system with multiple dielectric resonators arranged in different directions, which was found to be very effective for the on-line measurement of the fiber orientation of the paper sheets produced in the high-speed manufacturing machine.

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