ACCURATE FLOW FRONT ESTIMATION USING AREA-ARRAY SENSOR AND IMPLICIT INTERFACE FUNCTION

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1 Introduction

Due to the unexpected resin flow process in VaRTM, an un-impregnated area called a dry spot sometimes occurs in complicated composite structures.

In recent years, various methods for monitoring resin flow have been proposed. Optical fiber methods [1-3] use changes in the refractive index or the strength of reflected light, to monitor the resin arrival to the sensor location. However, this method only measures resin arrival at the point (or tip) of the optical fiber. Many embedded optical fibers are required for monitoring a wide area. Moreover, it is difficult to monitor dry spots that occur between two adjacent optical fibers. Although fiber bragg grating (FBG) sensors were developed for monitoring distributed points [4, 5], the FBG sensors still only measure along the optical fiber line. The expensive equipment required for optical spectrum analyzers and the possibility of decreasing the strength of the part or interfering with the smooth resin flow due to embedded optical fibers are also problematic.

Permittivity or conductivity methods were also proposed for monitoring resin flow [6]. The high relative permittivity of polymer resin or its conductivity enables the monitoring of the resin arrival to the sensor location. However, most of these sensors are also point sensors. Although linear sensors were proposed using electrical conductivity change [7-9] or electrical time-domain reflectometry [10], they measure only along the line. Moreover, the resin flow is assumed to flow in one direction; thus the method is not suitable for multiple inlets. Array or grid sensors are proposed by the authors for monitoring a resin impregnated area [11, 12] and also for cure monitoring [13]. These methods have the advantage of reducing wiring cables, and it is possible to monitor an arbitrary resin flow process. However, since the conventional grid sensors are still collections of point sensors at cross points, they have an un-sensing or at least a bias of sensitivity area depending on the location. Thus, it is possible they can fail to detect dry spots. Although full-field monitoring is possible using a camera or video [14], it is not applicable when the mold is not transparent.

In this study, a full-field monitoring method was proposed using an area-sensor array for monitoring the resin flow process and detecting small dry spots during the VaRTM process. Each area sensor was a square shape and measured the ratio of the resin impregnated area to the corresponding total area. These squared area sensors were aligned without any un-sensing space and covered the whole area of the film. An accurate flow front identification scheme is also constructed by combining area-array sensor and implicit interface function.

2. Area-sensor array for monitoring of resin flow

A flexible substrate was used as a base for an area-sensor array to measure the resin flow front figuration. A pattern of electrodes and wirings made by photolithography is shown in Fig. 1. The configuration of the film was 200×200 mm^2. The thickness of the sensor including the copper for the electrode and polyimide base was 13 μm. Because of such a thin film, the sensor film was very flexible, and could easily be attached to complicated or curved molds. Moreover, the film was stacked between the composite laminates and the mold. Flow interference and decreased strength may not occur in the cured composites.

Wiring was attached to the back of the film and connected to interdigital electrodes on the other side by through-hole connection. The sensors were aligned in a matrix or grid, and the wiring of the sensors was divided between rows and columns. In this study, the wires 1, 2, …, 5 were used to identify the longitudinal connections, and A, B, …, E identified the horizontal connections. Thus, there were a total of 25 sensors and 10 wires. When the wires "5" and "D" were connected to a measuring instrument, a capacitor was formed at the cross-section marked with a black square as shown in Fig. 1. In the same way, an arbitrary point can be measured by switching the wiring numbers. By this grid sensing, there were only (m + n) wires for ($m \times n$) measurement points; which was suitable for multi-point sensing. Since the sensors and wiring are easily fabricated simultaneously using photolithography, the manufacturing cost does not increase with an increase in the number of measurement points. Therefore, installing multiple sensors was much easier than installing conventional sensors, which required the embedding of many sensors and wires. Although the accuracy increases as the number of sensors increases, the number of sensors has to be limited to minimize or avoid complicated wiring, accommodate the available relay circuit capacity, and avoid decreasing the sampling rate.

The sensor had capacitive interdigital electrodes. Each sensor had a squared sensing area, and the impedance of the sensor changed to correspond with the impregnated area ratio of the sensor area. This enabled us to measure the area impregnated with resin for each squared section. The entire film surface was covered with these squared interdigital electrodes without any un-sensing space; thus it allowed the full-field monitoring of the resin flow, and was expected to identify the precise flow front and detect any small dry spots that occurred anywhere on the film.

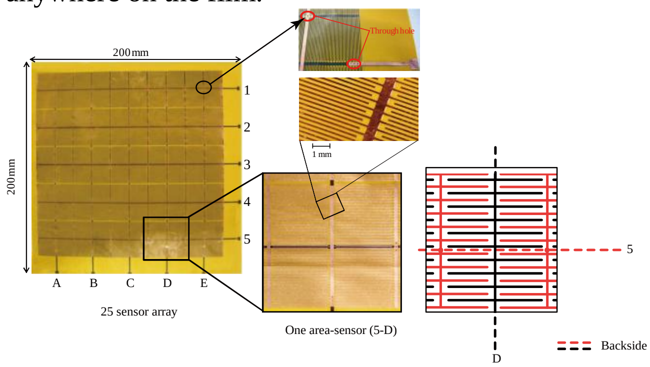

Fig. 1 Area-sensor array film for full field monitoring of resin flow.

3. Scheme of full-field flow monitoring

Since there is a linear relationship between the impedance change ratio and the impregnated area ratio, the impregnated area can be estimated using the impedance change ratio at each sensing area. However, even if the distribution of the impregnated area ratios of each area sensor is known, the precise flow front is unknown. In this section, using the impregnated area ratios of each area sensor, the flow front is estimated to match the estimated impregnated area and each measured impregnated area ratio.

First, the impregnation factor F_{ij} at sensor i-j is defined as follows:

$$F_{ij} = \frac{\Delta\left|Z_{ij}\left(S_{\mathrm{I}}/S, T\right)\right|}{\Delta\left|Z_{ij}\left(1, T\right)\right|}. \tag{1}$$

The factor F_{ij} corresponds to S_{I}/S: 0 before impregnation, and 1 at full impregnation of the sensor i-j. By measuring the value $\Delta|Z(1, T)|$ using the same electrode beforehand, real-time measuring of F_{ij} is possible.

We know the impregnated area ratios at each sensor area by obtaining the impregnation factor F_{ij} at each electrode. Next, using the factor F_{ij}, cubic spline interpolation is conducted, and we obtain the surface of the factor $F(x,y)$ at an arbitrary location where the x-y coordinate is defined on the in-plane of the film as shown in Fig. 2(i). It is assumed that the impregnated area figuration of one sensor is affected by the adjacent impregnated sensor area, and the flow front is a smooth curve.

The area of $F(x,y)$ over the threshold F_{t} in the sensor i-j domain corresponds to the estimated impregnated area ratio $FE_{ij}(F_{\mathrm{t}})$ in the sensor i-j as shown in Fig. 2(ii):

$$FE_{ij}\left(F_t\right) = \frac{\int\int_{\Omega_{ij}} H\left(F - F_t\right) dxdy}{S_{ij}}, \tag{2}$$

where H is Heaviside step function, S_{ij} is the sensor i-j area, Ω_{ij} indicates the sensor i-j region.

Finally we determine the threshold F_{t} by minimizing the residual sum of squares between the measured impregnated area ratio F_{ij} and estimated impregnated area ratio $FE_{ij}(F_{\mathrm{t}})$ as follows:

$$F_t^{opt} = \arg\min_{F_t}\left(\sum_{i,j}\left(F_{ij} - FE_{ij}\left(F_t\right)\right)^2\right). \tag{3}$$

The flow front is expressed by the implicit interface function $\phi=F(x,y)-F_t=0$. Since the cubic spline function $F(x,y)$ has the smooth curvature and the threshold F_t is constant over the all sensors, the implicit interface $\phi=F(x,y)-F_t=0$ satisfies the continuation of slope at the interface of the adjacent sensors. However, it is noted that the function $F(x,y)$ outside of the sensor grid is constructed by extrapolation, which means the estimation accuracy may become lower compared with the inside of the grid.

For example, if the measured impregnated ratio F_{1A} is 0.6 using the impedance change ratio at the sensor 1-A, the estimated impregnated area is drawn with a smooth line in accordance with 60 % impregnation of the sensor 1-A. Thus the estimated impregnated area matches the measured impregnated area ratio using the area-sensor array. The area that is not impregnated, where F_{ij} is less than 1.0, is not ignored, and small dry spots will be detected.

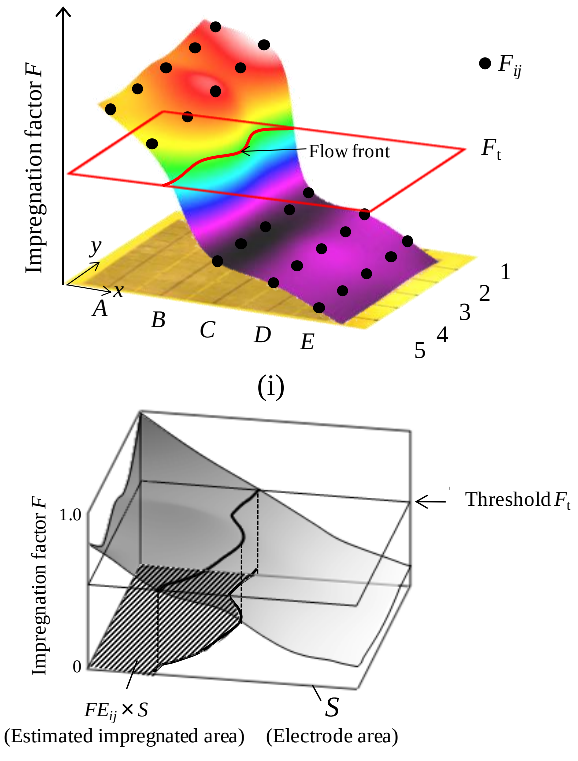

Fig. 2 The schema for identifying the impregnated area.

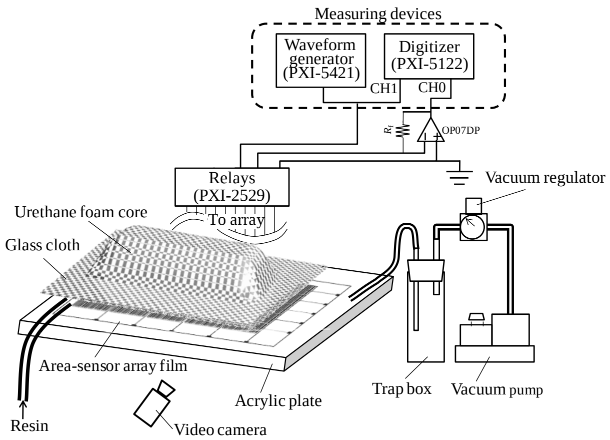

Fig. 3 Experimental setup of flow monitoring with the area-sensor array and the zero potential method.

4 VaRTM flow monitoring experiments

4.1 Experimental procedures

The experimental setup is shown in Fig. 3. The area-sensor array film is placed on the acrylic plate and eight layers of 1K glass cloth (Molymer SSP, YEM1801) are stacked on the film. The urethane foam core is inserted between the fourth and fifth layer. The experiments were carried out by impregnating the glass fabric with unsaturated polyester resin (DH material, Sundhoma PC-184-C).

A wave-generator (National Instruments, PXI-5421) generated an 800 Hz and 2 Vpp sine wave, and the impedance was measured using a digitizer (National Instruments, PXI-5122). Switching was carried out using a 4×32 matrix relay circuit (National Instruments, PXI-2529) as shown in Fig. 8. The impedance was measured 30 times at 800 Hz at each sensor and the average values were used for estimating the impregnated area ratio. The averaging times of 30 was selected to complete the measurements of 5×5 sensors within several seconds.

Measuring, switching, and drawing procedures of the flow front including the cubic spline interpolation were conducted using National Instruments LabVIEW 8.5. The flow process was also monitored using a digital video camera as a reference.

4.2 Results and discussion

Figure 4 shows the impedance change ratio of the sensor 1-A during VaRTM impregnation. The abscissa gives the elapsed time from starting the measurements. By using the zero potential method, the 1-A impedance does not change after full impregnation. The noise in the impedance change ratio is also suppressed.

Figure 5 shows the picture recorded by the digital video camera in the left figure, and the estimated impregnated area within the sensor-placed regions in real time using the proposed area-sensor array film in the right figure. The red grid indicates the sensor location in the area-sensor array film, and the blue line indicates the flow front in the picture. Figure 5(i) shows the impregnation at (i) t=1/4 T and (ii) t=1/2 T, where the impregnation starting time is set at t=0, and the full impregnation is set at t=T.

From the recorded picture in Fig. 5 at (i) t=1/4 T, it was observed that the resin flow under the urethane foam core was delayed compared with the side areas: the sensor 3-A, which was located inside the urethane foam core region, was not impregnated, whereas the sensors 2-A and 4-A were impregnated. The estimated results using the area-sensor array also clearly indicate this resin flow delay. Subsequently, the two flows on both sides of the foam core impregnated faster than the central flow around the core region, and the two side flows touched before the center area was impregnated with resin. Consequently, a dry spot occurred at (ii) t=1/2 T around the core region. The measured results using the sensor array also detected the dry spot occurring in 3-C.

When looking at the detail of the estimated impregnated area, there is some error compared with the recorded picture: 1-A in Fig. 5(i) or 5-B in (ii) for example. This is because of the limitation of cubic spline interpolation, and the lack of sensing area independence. However, the overall estimated flow front figuration was quite accurate considering only 5×5 sensors were used. If the number of sensors was increased, a more accurate flow front could be estimated.

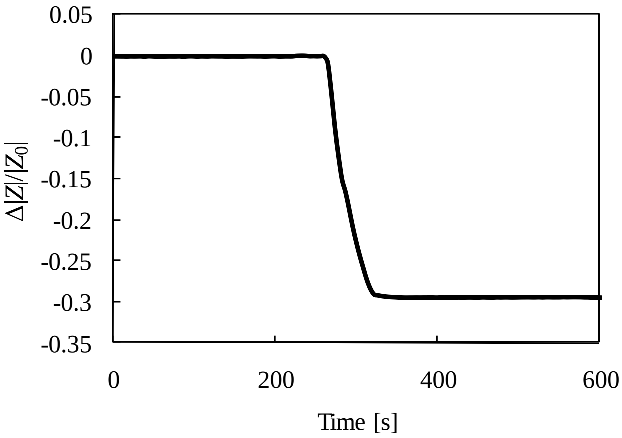

Fig. 4 Impedance change ratio of the electrode 1-A during VaRTM.

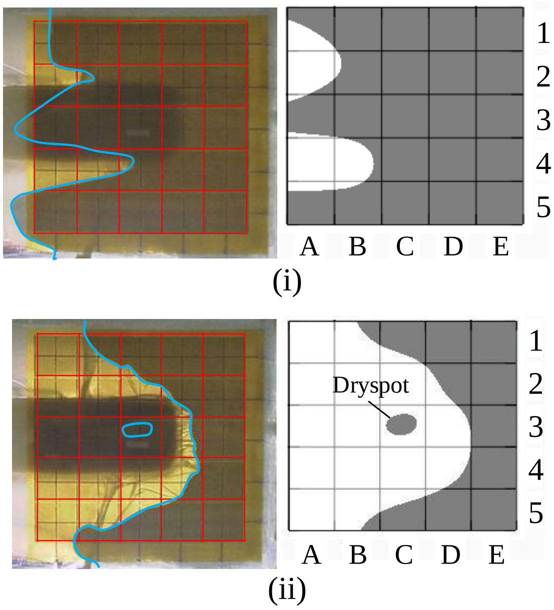

Fig. 5 Impregnation view and impregnated area measured by the impedance change ratio. Resin flowed from left to right. (i) t = 1/4 T, (ii) t = 1/2 T.

5. Conclusions

An area-sensor array was proposed for full-field monitoring of resin flow during the VaRTM process. Each area sensor measured the impregnated area ratio for the corresponding sensor area, and the sensor array enabled us to know the distribution of the impregnated area ratios. By minimizing the residual sum of squares between the measured and estimated impregnated area, the precise flow front or dry spot figuration was estimated using implicit interface function.

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