DATA ASSIMILATION FOR MONITORING RESIN TRANSFER MOLDING OF COMPOSITE MATERIALS

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Abstract

Vacuum assisted Resin Transfer Molding (VaRTM) is widely used for molding of composite structures. However, ensuring complete impregnation of the resin into fiber materials is difficult and it sometimes causes the formation of un-impregnated regions, called dry spots. Due to the poor quality of a VaRTM process, its application is currently limited. Therefore, monitoring of the resin flow during the process is necessary to predict and prevent the formation of dry spots. This paper presents a method to observe resin impregnation in a VaRTM process without embedding sensors into composite structures. Planar-shaped sensor electrodes arranged on a molding tool are used to measure electrical capacitance values from pairs of the electrodes. These measurements are combined with the numerical simulations of a VaRTM process to estimate the state of the resin impregnation. This method is based on the ensemble Kalman filter (EnKF), known as a sequential data assimilation technique. The proposed method was examined by a numerical experiment. In the numerical experiment, the resin-impregnated region and the permeability distribution of a fiber preform were estimated concurrently and it was confirmed that the decrease of flow velocity in a low permeability region could be estimated.
**Background**

◆ VaRTM (Vacuum assisted Resin Transfer Molding)

Monitoring of resin flow is necessary.

**Recent studies for flow monitoring**

Invasive sensing

- Optical fiber sensor etc.

- Embedding sensors in composites may affect on material strength.

Non-invasive sensing

- Resistive sensor etc.

- Measurement range is limited to small area near the sensor.

Existing sensors are not suitable for monitoring of thick part processing.
Data assimilation for flow monitoring

Requirements for flow monitoring of thick part processing
- Non-invasive sensor
- Applicability to three dimensional resin flow monitoring
  ➡️ Conflicting with each other...

Proposed method: data assimilation

- Non-invasive capacitive measurements
- Stochastic simulation of resin flow

Integration

Sequential data assimilation by the Ensemble Kalman Filter

Objectives

Development of 3 dimensional resin flow monitoring method by an approach integrating sensor measurements and numerical simulations

- Proposing a sensor that can obtain the information of three dimensional resin flow from a surface of a structure
- Developing a method to estimate resin flow from the measured values and numerical simulation
- Investigating the validity of the proposed method by numerical experiments
Overview of the proposed method

◆ Flow monitoring by an approach integrating electrical measurements and numerical simulations

(1) Capacitive sensors

(2) Stochastic simulation
Uncertainty in a VaRTM process is simulated by using multiple simulators.

Sequential data assimilation by the
(3) Ensemble Kalman Filter

Three dimensional resin flow is estimated.

(1) Electrical capacitance sensor

◆ Multiple electrical capacitance measurements

Glass fabrics
Resin
Electrical capacitance
Molding tool
Electrodes

Capacitance: \( \mathbf{c}_i = (c_{i1}, \ldots, c_{iM})^T \)

M: No. measurements

Change with resin flow

Inversion

Resin distribution: \( \mathbf{f}_i = (f_{i1}, \ldots, f_{iN})^T \)

N: No. nodes

\( 0 \leq f_i \leq 1 \)

Resin flow represented by \( f \)

A vector \( \mathbf{c}_i \) provides information about 3D resin flow. However, insufficient to reconstruct the resin distribution.
(2) Stochastic Simulation: Part 1

(i) Simulation of homogeneous model

Darcy’s law

\[ \mathbf{u} = -\frac{K}{\phi \mu} \nabla p \]

\( \mathbf{u} \): Resin velocity, \( p \): Pressure, \( \phi \): Porosity, \( \mu \): Viscosity

Permeability is spatially constant.

(ii) Simulation of inhomogeneous model

Spatial variations of permeability:

\( \mathbf{K}(\mathbf{x}) = \overline{\mathbf{K}} \{ 1 + \alpha(\mathbf{x}) \} \)

Permeability is not uniformly-distributed.

Discretization \( \alpha(\mathbf{x}) \): Deviation

Permeability distribution vector \( \alpha = (\alpha_1, \alpha_2, \ldots, \alpha_{N_e})^T \)

\( N_e \): number of finite elements

(2) Stochastic Simulation: Part 2

(iii) Stochastic simulation of inhomogeneous model

Assuming a covariance function of the deviation \( \alpha(\mathbf{x}) \), samples of spatially correlated permeability distribution are generated.

\[ \text{Cov}_{\alpha}(\mathbf{x}_i, \mathbf{x}_j) = \sigma_\alpha^2 \exp \left( \frac{-|x_i - x_j|^2}{\eta_x^2} \right) \exp \left( \frac{-|y_i - y_j|^2}{\eta_y^2} \right) \exp \left( \frac{-|z_i - z_j|^2}{\eta_z^2} \right) \]

\( \eta_x, \eta_y, \eta_z \): Correlation lengths, \( \sigma_\alpha \): Spatial variation

Samples of permeability field \( \{ \alpha_0^{\text{est}(1)}, \ldots, \alpha_0^{\text{est}(L)} \} \)

Initial state vectors \((l = 1, \ldots, L)\)

\[ \mathbf{f}_0^{(l)} = \left( \begin{array}{c} \mathbf{f}_0^{(l)} \\ \alpha_0^{(l)} \end{array} \right) \]

\( \mathbf{f}_0 \): Resin distribution \( \alpha_0 \): Permeability distribution

Stochastic simulation

\[ \mathbf{f}_l^{*{(l)}} = F(\mathbf{f}_{l-1}^{*{(l)}})(l = 1, \ldots, L) \]
Numerical simulation of VaRTM

- Darcy’s law
  \[ \mathbf{u} = -\frac{K}{\phi \mu} \nabla P \]
  \( K \): permeability tensor
  \( \mathbf{u} \): velocity,
  \( P \): pressure
  \( \phi \): porosity,
  \( \mu \): viscosity

- Continuity equation
  \[ \nabla \cdot \mathbf{u} = 0 \]

- Advection equation of fill factor
  \[ \frac{\partial f}{\partial t} + \nabla \cdot (f \mathbf{u}) = 0 \]

\[ f : \text{fill factor} \]
\[
\begin{cases} 
  f = 0 & : \text{Unfilled} \\
  0 < f < 1 & : \text{Partially filled} \\
  f = 1 & : \text{Filled} 
\end{cases}
\]

\[ \text{Initial condition} \hspace{1cm} \text{Computation of pressure distribution} \hspace{1cm} \text{Update fill factor} \hspace{1cm} \text{Fin.} \]

\[ \text{Finite element method} \]
\[ [C] \frac{df}{dt} + [K]\{f\} = 0 \]

(3) Ensemble Kalman Filter (EnKF)

- Flow monitoring integrating simulation and measurements

\[ \text{Stochastic simulation} \]
\[ L \text{ independent simulations} \]
\[ \mathbf{f}_{i*}^{f(l)} = F\left( \mathbf{f}_{i-1*}^{f(l)} \right) \]
\( \mathbf{f}_{i*} \): State vector,
\( \mathbf{f}_{i-1*}^{f(l)} \): L independent simulations
\( F \): Simulation operator

\[ \text{Observation equation} \]
\[ \mathbf{c}_{i} = \mathbf{h}(\mathbf{f}_{i*}^{\text{true}}) + \text{noise} \]
\[ \approx \mathbf{h}(\mathbf{f}_{i*}^{\text{true}}) + \mathbf{S}_{i}(\mathbf{f}_{i*}^{\text{true}} - \mathbf{f}_{i*}^{\text{true}}) + \mathbf{v}_{i} \]
\( \mathbf{h} \): Observation operator
\( \mathbf{S}_{i} \): Sensitivity matrix
\( \mathbf{v}_{i} \): Observation error vector

\[ \text{Ensemble Kalman Filter} \]
\[ \text{Update } \mathbf{f}_{i*} \text{ and } \mathbf{a}_{i} \text{ by measurements } \mathbf{c}_{i} \]
**Numerical experiments**

**Forward simulation**

- Figure (a): Center view of a resin flow simulation.
- Figure (b): Front side view of a resin flow simulation.

**Estimation by the EnKF**

- Equation: $K(x) = K_0[1 + \alpha(x)]$
- Initial ensemble: $\{\alpha_0^{(1)}, \ldots, \alpha_0^{(L)}\}$
- Ensemble forecast: $f_{t-1}^{\text{est}(l)}$ ($l = 1, \ldots, L$)
- Update: $f_t^{\text{est}(l)} = F(f_{t-1}^{\text{est}(l)})$
- Kalman gain: $G_t$.

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**Results of resin flow estimation: (1)**

**Forward simulation**

- Figure: Simulation of resin flow.

**Estimation by the EnKF**

- Equation: $f_t^{\text{true}} = f_t^{\text{est}} = \frac{1}{L} \sum_{l=1}^{L} f_{t-1}^{\text{est}(l)}$
- True: $f_t^{\text{true}}$
- Flow front
- Estimation: $f_t^{\text{est}} = \frac{1}{L} \sum_{l=1}^{L} f_{t-1}^{\text{est}(l)}$

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- Resin inlet
- Instrumentation
- Results of resin flow estimation: (1)
Results of resin flow estimation: (2)

Forward simulation

Estimation by the EnKF

(b) Front side

Results of permeability estimation: (1)

Forward simulation

Estimation by the EnKF

Decrease in velocity in a low permeability region could be estimated.

\[ \frac{1}{L} \sum_{i=1}^{\ell} f_{est(i)} \]
Results of permeability estimation: (1)

Results of permeability estimation: (2)

Permeability distribution was estimated simultaneously.
Conclusions

Bridging the gap between measurements and simulation

- Flow monitoring method integrating electrical measurements and numerical simulations by the EnKF was developed.
- In a numerical investigation, it was confirmed that the resin flow front and permeability field can be estimated during a VaRTM by the proposed method.