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BEM simulation of 3D updated resin front for LCM processes

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Abstract

The use of composite materials in large structures has increased in recent years. Aircraft industry has recently begun to investigate the field of Liquid Composite Molding (LCM) through research programs because of its ability to produce large parts at low cost. The resin motion through the fibrous preform is described using Darcy's law and mass conservation. The 3D flow is solved numerically using the Boundary Element Method (BEM). The simulations are performed using an updated lagrangian mesh in isothermal conditions. The numerical model is assessed by comparing computed results with the analytical solution in the case of radial injection from a spherical inlet.

1 Introduction

Composite materials have been used in the aircraft industry over the past three decades for their excellent specific mechanical properties. Large structural parts made of resin/fiber composites require specific forming processes. The traditional prepreg autoclave process produces high quality parts, but involves heavy manufacturing cost due to autoclave investment and use of high value added raw materials. As an alternative, recent technologies in Liquid Composite Molding (LCM) have become established recently under the designation of infusion processes. Liquid Resin Infusion (LRI) is one of them. It consists in forcing the liquid resin to circulate transversally into the dry preform using a distribution medium, consecutively to the vacuum application [1].

Prediction of resin flow during the infusion filling stage requires a full three-dimensional model in order to take into account the lag due to the distribution medium. Previous works revealed the adequacy of Boundary Element Method (BEM) solving the Darcy flow [2-4]. It was performed assuming a two-dimensional flow, neglecting the impregnation through the thickness.

The present paper is focused on a three-dimensional numerical modeling of the Newtonian isothermal flow using constant Boundary Elements. Combining Darcy's law with incompressibility equation leads to Laplace equation which is solved using BEM at each step time on an updated lagrangian mesh. Preliminary results are presented, i.e. BEM simulations performed in the case of central injection. Computed results are compared with an analytical solution.

2 Governing equations

2.1 Modeling assumptions

The liquid resin flow through homogenous and not deformable porous medium (i.e. fibrous reinforcement) is modeled by the phenomenological Darcy's law [5] together with incompressibility equation. The filling stage is assumed to be isothermal.

2.2 Darcy's law

The average velocity \vec{v} is proportional to the pressure gradient according to the following equation:

$$\vec{v} = -\frac{[K]}{\mu} \vec{\nabla} p \quad (1)$$

where $[K]$ is the permeability tensor, p the resin pressure and μ the liquid resin viscosity. Combining Equation 1 and incompressibility equation gives:

$$\vec{\nabla} \cdot \left(-\frac{[K]}{\mu} \vec{\nabla} p \right) = 0 \quad (2)$$

For sake of simplicity, we assume in this paper that the principal orthogonal axis of the reinforcement coincides with the reference coordinates system, such as $[K]$ reduces to diagonal matrix. Equation 2 can then be reduced to Laplace equation in the isotropic equivalent domain by stretching the coordinates. In the Cartesian coordinate system, the equivalent coordinates \vec{x}_e may be deduced from the physical coordinates \vec{x} using the following transformation:

$$x_{e_i} = \sqrt{\frac{K_e}{K_i}} x_i \quad (3)$$

where K_i is a principal value of $[K]$ and K_e the equivalent permeability given as $K_e = \sqrt[3]{K_1 \cdot K_2 \cdot K_3}$. In the isotropic equivalent domain, Equation 1 and Equation 2 reduce simply to:

$$\vec{v}_e = -\frac{K_e}{\mu} \vec{\nabla} p \quad (4)$$

$$\Delta p = 0 \quad (5)$$

2.3 Analytical solution

Following the approach introduced by Adams et al. [6], an analytical solution is used to calculate the evolution of the flow front versus time. Computations are performed in the isotropic equivalent system, using the equivalent permeability K_e and the spherical injection gate of radius r_{0e} . A constant pressure injection p_0 is applied, so that the macroscopically resin front shape is spherical of radius r_{fe} . In such configuration the resin pressure varies only in the radial direction according to:

$$\frac{p - p_f}{p_0 - p_f} = 1 - \frac{\frac{1}{r_{0e}} - \frac{1}{r_e}}{\frac{1}{r_{0e}} - \frac{1}{r_{fe}}} \quad (6)$$

Substituting the expression of the gradient pressure into Darcy's law and introducing the system porosity ε gives the radial component of the front velocity v_{fe} :

$$v_{fe} = \frac{K_e}{\mu \varepsilon} \frac{(p_0 - p_f)}{r_{fe}^2 \left(\frac{1}{r_{0e}} - \frac{1}{r_{fe}} \right)} \quad (7)$$

The evolution of the flow front is governed by the following differential equation:

$$v_{fe} = \frac{dr_{fe}}{dt} = \frac{K_e}{\mu \varepsilon} \frac{(p_0 - p_f)}{r_{fe}^2 \left(\frac{1}{r_{0e}} - \frac{1}{r_{fe}} \right)} \quad (8)$$

Finally, the time dependant flow front position can be deduced integrating the previous equation during the filling stage. This leads to the following solution:

$$\left[\frac{r_{fe}}{r_{0e}} \right]^2 \left[2 \frac{r_{fe}}{r_{0e}} - 3 \right] + 1 = 6 \frac{K_e (p_0 - p_f)}{\mu \varepsilon r_{0e}^2} t \quad (9)$$

Equation 9 gives immediately the flow front which is spherical in shape for an isotropic reinforcement. For the orthotropic case, the reciprocal transformation is applied to give the three semi-axis of the flow front which is ellipsoidal in shape.

3 Numerical simulation

3.1 Boundary Element Method

The calculation domain is delimited by its boundary $\Gamma = \Gamma_p \cup \Gamma_q$. A known value of pressure \bar{p} (resp. normal pressure gradient \bar{q}) is prescribed on the boundary surfaces Γ_p (resp. Γ_q). Equation 4 is multiplied by the Green function p^* . Integrated by parts twice over the calculation domain and using Green's theorem leads to the well-known Somigliana equation [7, 8]:

$$c_i p_i + \int_{\Gamma} p q^* d\Gamma = \int_{\Gamma} p^* q d\Gamma \quad \text{with } c_i = \frac{\theta}{2\pi} \quad (10)$$

where p_i is the value of the pressure at a point M_i located on the boundary (which is supposed to be smooth), q^* the pressure gradient associated with p^* and θ is the internal angle of the corner in radians. For a three-dimensional domain, p^* and q^* are given as:

$$p^* = \frac{1}{4\pi r} \quad \text{and} \quad q^* = \frac{1}{4\pi} \frac{-\vec{r} \cdot \vec{n}}{r^3} \quad (11)$$

where r is the distance from the point M_i of application of the Dirac delta function to any point under consideration. Meshing the boundary into N constant boundary elements and applying Equation 10 gives:

$$c_i p_i + \sum_{j=1}^N p_j \int_{\Gamma_j} q^* d\Gamma = \sum_{j=1}^N q_j \int_{\Gamma_j} p^* d\Gamma \quad (12)$$

Introducing the $N \times N$ matrix H and G , Equation 12 is then transformed into:

$$\sum_{j=1}^N p_j H_{ij} = \sum_{j=1}^N q_j G_{ij} \quad (13)$$

$$\text{where } H_{ij} = \frac{1}{2} \delta_{ij} + \int_{\Gamma_j} q^* d\Gamma \quad \text{and} \quad G_{ij} = \int_{\Gamma_j} p^* d\Gamma$$

Finally, Equation 13 is reordered to take the form of a linear system as:

$$AX = F \quad (14)$$

where X is the vector of N unknowns, A is a $N \times N$ matrix obtained by reordering H and G . F is the known vector computed from the boundary conditions, H and G matrix.

3.2 Fluid domain updating

The fluid domain is continuously expanding as it flows, constraining to update the resin flow front. The filling stage is regarded as a succession of quasi-steady states, so that the geometry is redefined at each time step. Unknown pressures p and normal pressure gradients q are calculated using Equation 14. Nodes on the moving boundary are relocated using a backward Euler integration scheme:

$$\vec{x}(t + \Delta t) = \vec{x}(t) + \Delta t(\vec{v} \cdot \vec{n})\vec{n} \quad (15)$$

Combining Equation 15 and Equation 4 yields to:

$$\vec{x}(t + \Delta t) = \vec{x}(t) - \Delta t(K_e \frac{q}{\mu} \vec{n}) \quad (16)$$

The procedure updates the resin flow front, but induces confined mesh degeneration. To overcome this difficulty, an additional adjustment is performed relocating the nodes in contact with the mold.

3.3 Algorithm

The implemented algorithm is summarized below:

- Initial computation domain is meshed.
- Stationary boundary conditions p or q are applied on each BEM element.
- Nodes coordinates are transformed according to Equation 3.
- Normal pressure gradients q are calculated according to Equation 14.
- Normal pressure gradients are prescribed on each node averaging values from surrounding elements.
- Nodes on the moving boundary are relocated according to Equation 16. Nodes in contact with the upper mold wall are relocated according to a homogenization procedure.
- New normal pressures p and normal pressure gradients q are calculated next steps. The three last steps are repeated until the allotted mold-filling time is reached.
- Nodes coordinates are transformed according to the reciprocal transformation.

4 Validation of numerical simulation

4.1 Boundary conditions

The simulation consists in propagating the resin front into an anisotropic reinforcement characterized by its permeability tensor $[K]$ and its porosity ε . A constant pressure p_0 is prescribed at the spherical inlet of radius r_0 . On the flow front, the pressure p_f is constant and set by the vacuum pump. Processing and rheological parameters assigned are referenced in Table 1. They keep close to the LRI process conditions but the distribution medium is not taken into account as a first approach.

Figure 1 shows the boundary conditions prescribed on the boundary of the initial fluid domain. The non penetration condition is assumed assigning $\vec{q} = 0$ at the upper mold wall.

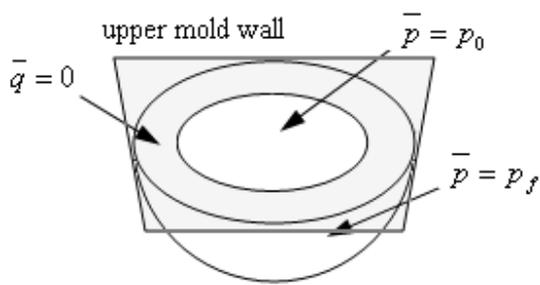


Figure 1: Boundary conditions

$[K]$	(10^{-11} m^2)	μ	(Pa.s)	ε	
$\begin{bmatrix} 4 & 0 & 0 \\ 0 & 2 & 0 \\ 0 & 0 & 1 \end{bmatrix}$		0.1		0.5	
p_0	(Pa)	p_f	(Pa)	r_0	(m)
1.10^{-5}		-1.10^{-5}		3.10^{-2}	

Table 1: Rheological and processing parameters

4.2 Comparison with analytical solution

For symmetry reasons, the simulation is performed on a quarter domain meshed using 540 elements as shown in Figure 2. The step time is set at 10^{-2} s. CPU time for the complete simulation is around one hour on Intel® Core™2 Duo CPU using Matlab® environment. The computed flow fronts are in fair agreement with the analytical one as shown in Figure 3. At 10 s elapsed time, the deviations between the numerical and analytical flow fronts positions do not exceed 1%. Prolongating the simulation until 60 s gives deviations around 3%, due to the gradual mesh degeneration as the iterations go along. Figure 4 illustrates the flow front evolution during the filling stage, comparing the front shapes at $t=0.5$ s and $t=10$ s.

The initial mesh generation is performed on the equivalent isotropic domain. In order to assess the mesh effect on the numerical method, some simulations have been carried out meshing the physical domain. Deviations are all the more important that the permeability values are different. This is due to the transformation from Equation 3 which stretches the mesh, degenerating elements before any calculation.

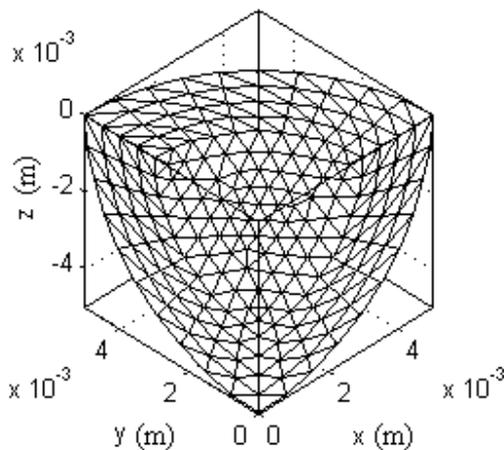


Figure 2: Initial meshed domain

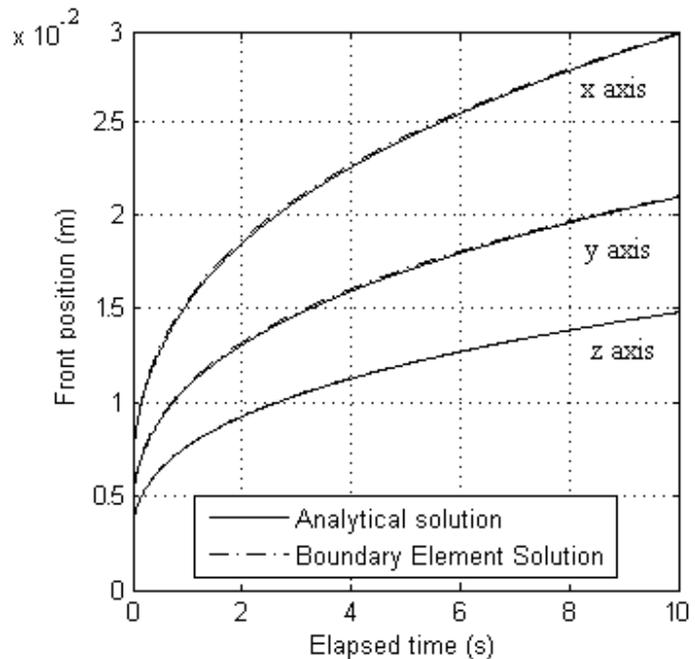


Figure 3: Comparison with analytical solution

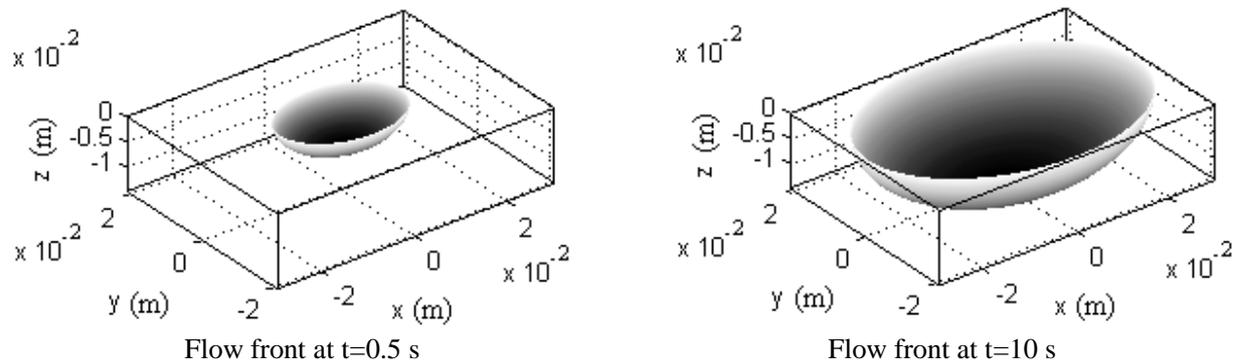


Figure 4: Flow front computed for $t=0.5$ s and $t=10$ s

4 Conclusions

The resin flow front propagation is accurately simulated using a backward time-stepping algorithm. This technique is efficient for short distances of impregnation, giving a high accuracy of the front position. However, it is unsuitable for larger distances, since the calculated position becomes inaccurate as soon as elements are degenerated. Including remeshing procedures is possible but could be time consuming.

Finally, the implementation of the present numerical method becomes tedious for dividing and merging resin fronts resulting from interior obstacles or multi-injection ports. Future works will investigate the combination of Boundary Element Method with fixed grid techniques such as the Level Set method.

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