Improving computational efficiency in LCM by using computational geometry and model reduction techniques

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\textbf{Abstract.} LCM simulation is computationally expensive because it needs an accurate solution of flow equations during the mold filling process. When simulating large computing times are not compatible with standard optimization techniques (for example for locating optimally the injection nozzles) or with process control that in general requires fast decision-makings. In this work, inspired by the concept of medial axis, we propose a numerical technique that computes numerically approximate distance fields by invoking computational geometry concepts that can be used for the optimal location of injection nozzles in infusion processes. On the other hand we also analyze the possibilities that model order reduction offers to fast and accurate solutions of flow models in mold filling processes.

\textbf{Introduction}

In this work we pursue a fast and efficient method to locate an (approximate) optimal location for injection nozzles and vents in LCM processes. To this end, we consider the following main assumptions:

- We try to avoid to simulate processes based on Darcy's law (just to try to be as efficient as possible)
- As a first approach, we consider homogeneous reinforcement with therefore homogeneous (and isotropic) permeability tensor. This will be later refined.
- As a first approach, we consider the process linear and reversible. This means than an hypothetical process in which injection is made from the vents would locate the position of the nozzles.

Under these hypothesis, it seems reasonable to assume that the medial axis of the geometry of the piece is a good indicator\textsuperscript{4} of the position of injection nozzles. The medial axis \cite{1} of an object is the set of all points having more than one closest point on the object's boundary.

Since non-isotropic reinforcements would alter the velocity field during the process, and it is not clear how this would affect the position of the medial axis, we propose here an alternate algorithm to compute the medial axis that is amenable to changes in the case of non-isotropic reinforcements. This algorithm is based upon the use of level sets.

\textsuperscript{4}Still with some limitations. For instance, the medial axis of an object with sharp corners touches its boundary, thus provoking nozzles and vents to coincide at particular locations.
An algorithm based on the use of level sets

Following [7], we will describe the resin advancing front as the zero set of an implicit function $\phi$. The evolution of this implicit function under an external velocity field will be given by

$$\phi_t + \mathbf{v} \cdot \nabla \phi = 0.$$  

Here, sub-index indicate a partial derivative with respect to that variable.

If, under the simplifying assumptions mentioned in the introduction, we assume that the velocity field at the resin flow front is normal to the implicit function $\phi$ itself, $\mathbf{v} = a\mathbf{n}$, we will have

$$\phi_t + a|\nabla \phi| = 0,$$

and, since our ultimate goal is to compute an approximation to the medial axis, we are interested in computing a signed distance function, i.e., $|\nabla \phi| = 1$. For this it is sufficient to take $a = \text{cte}$. For simplicity we will take $a = 1$, so as to give

$$\phi_t = -a = -1.$$  

See Section 6.2 of [7] for details on the discretization of this equation.

In general, any method for the construction of a signed distance function could be useful to us. See [7], sections 7.3 to 7.5 on the basis of the Fast Marching Method. In Fig. 1 a representation of the evolution of the level set curves giving rise to the approximate location of injection nozzles is made. In Fig. 2 these curves along history are represented over the geometry of the mould.

If non-homogeneous reinforcements are considered, level set equations are modified accordingly, so as to still provide good approximations to the sought nozzle location, see Fig. 3.

Limitations and open questions

In Figure 1 an example of the evolution of a rectangle-shaped implicit function is depicted. It can be noticed that a very exact tracking of the interface is achieved. But the main goal of this work is to
Fig. 2: Evolution of the level set curves for the filling process of a rectangular mould.

Fig. 3: Evolution of the level set regions for the filling process of a rectangular mould with non-isotropic reinforcement.
determine the location of optimal placements for injection nozzles. Therefore, we are interested in
tracking the position of geometrical locations of merging fronts. For instance, if we inject from the
boundary of a circle, the flows will merge at the center. But if we inject from the boundary of an
ellipse, the fronts will merge at a straight line located at its central part. How to compute the position
and location of these lines, that later will play the role of injection nozzles, is a central part of this
work.

A naive but very fast way to compute this location is to take into account that for a finite element
located entirely on the "wet" or "dry" parts of the flow, \( \nabla \phi \) will take the same value at its four in-
tegration points. On the contrary, at elements receiving flows from two different fronts, the value of
\( \nabla \phi \) will change. These elements will contain a segment of the approximate medial axis. For this to be
effective, appropriate limits should be imposed on top of the CFL condition.

Model order reduction of RTM processes using LCM methods

Once an approximate yet accurate position for injection nozzles has been determined, appropriate
techniques should be used so as to obtain an as fast as possible simulation of the process. To this end
we employ model order reduction techniques, and in particular PGD methods [3] [2] [5] [6]. PGD
techniques allow for a fast and reliable simulation of parametric problems by considering these pa-
rameters as additional state-space variables and considering a separated representation of the solution
in terms of the mentioned parameters and physical coordinates.

The present work proposes to use this tool to optimize the main process parameters, the injection
flow rate and the injection/mould temperature, in order to ensure the complete filling of the mould
and reasonable fabrication costs (fabrication time, mould heating). To do so, we use the same methods
as in [5]: the two process parameters are introduced in the model as new coordinates, and the Proper
Generalized Decomposition method is used to solve the multiparametric model then obtained. By
this way, we are able to build computational vademecums, having the two parameters of interest as
variables, allowing the user to define the best compromise between injection time and process cost
(mould heating) while ensuring the complete filling of the mould.

The introduction of the temperature as a separated variable of the problem is quite natural and did
not introduce many difficulties. Concerning the injection flow rate, because it has an influence on the
time filling and is indirectly linked to the domain meshing by the filling simulation, its separation is
much more delicate and has to be treated with care.

This technique also allows for an in-plane/out of plane decomposition of the solution, when 51
layers of reinforcement are present [4]. It allows for very efficient computations, such as the one in
Fig. 4, whith more than 2 millions of equivalent FE degrees of freedom. This examples runs on a
laptop in 3 minutes under Matlab.

Conclusions

In this paper a novel methodology for a fast and reliable design and simulation of LC moulding pro-
cesses is developed. First, a technique based on the concept of level set allows for a fast and efficient
location of injection nozzles. After this approximate location, a model order reduction technique is
employed in order to simulate the process as fast as possible. Th global objective of this work is to
minimize as much as possible the process of mould design and decision making throughout the global
process of piece design.
Fig. 4: Model and pressure field for the filling process of a rectangular mould with holes. The piece is constructed with a 51-ply reinforcement.

References


