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FLOW PATTERN CONFIGURATION SPACES IN LIQUID COMPOSITE MOLDING PROCESS DESIGN

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SUMMARY: This paper challenges to define a novel configuration spaces, called *Flow Pattern Configuration Spaces* (FPCS) as a computational framework for LCM process design. The main interesting idea of using these spaces is the definition of the coordinate system by means of the process parameters related to the flow, instead of a customary Cartesian coordinate system. The proposed configuration space defines a mould mesh discretization using an alternative coordinate system. In the first part of the paper is proposed the filling time of each node as the configuration parameter. The resulting configuration space is called *Flow Pattern time Spaces* (FPTS). In this space, the flow fronts are ever straight lines or circles, permitting an easy understanding of the filling process. The same concept can be extended to other LCM time variables such as incubation time. In the second part, is proposed the distance for an interest point to each node as a configuration parameter. In this case, the desirable flow front shape must be a line or a circle due to the optimal flow front must be vent oriented flow. This space is called *Flow Pattern Distance Space* (FPDS). The proposed configuration spaces can be applied for whatever LCM process, whatever mould dimension and whatever gate and inlet shape. This work is extended in [7], where some application for optimization and control are outlined.

KEYWORDS: Liquid Composite Molding (LCM), configuration spaces, Resin Infusion (RI)

INTRODUCTION

Liquid Composite Moulding (LCM) processes include different techniques that can be divided in two main groups: techniques that need positive injection pressure like Resin Transfer Molding (RTM) and techniques that require negative injection pressure like, VARI (Vacuum Assisted Resin Infusion), VARTM (Vacuum Assisted Resin Transfer Molding) and SCRIMP (Seemann Composite Resin Infusion Molding Process). This second group is well-known as Resin Infusion (RI). This way of dragging the resin in the mould also determines the proper strategy to fill it and hence the optimal location and shape of the resin gate inlets and vents. In RTM, vent and gates are defined by points allocated in the mould meanwhile in RI processes the vent, gate or both can be points, lines and in many cases are located on the contour of the mould. For instance in VARI, the vent is typically allocated in the mould contour and the gate inlet in the inner part of the mould meanwhile in VART the locations are the opposite.

The success of filling and curing stages in liquid composite molding (LCM) depends on many variables such as locations of gates and vents, temperature distribution, flow rate, injection pressure, etc. Traditionally the selection of gate and vent locations in mold design was based on experience and trial and error attempts. In this sense, there are an amount of algorithms developed for RTM 2D moulds that are not valid for RI 2.5D moulds. For instance in [1, 2] was developed a simulation based Process Performance Index to measure the quality of the RTM filling process. These research studies have been conducted to define proper filling strategies based on gate-distance of the resin located on the flow front at different time steps. A good process should have short filling time and a vent-oriented flow with a desired resin flow pattern, see Fig.1. At a given time step, the distances from the nodes located on the resin flow front to the outlet are associated with the quality of the filling process. The standard deviation of those distances is used to evaluate the shape of the flow front. Those results are not useful for RI processes because the vent or the gate inlets can not be treated as points. In addition, also cannot be used in 2.5D moulds because the Euclidean distance does not measure properly the distance of the flow front nodes to the vent, moreover measures the straight line between them, restricting the applications of this index for RTM 2D moulds.

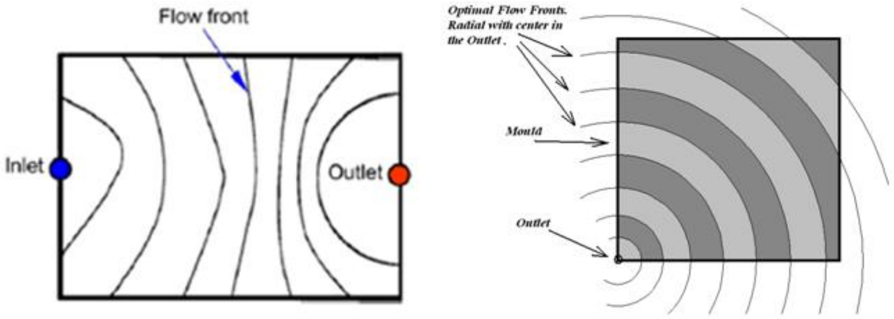


Fig. 1 Optimal vent oriented flow fronts and radial flow behaviour.

The tendency in more recent studies is to use the algorithms developed for RTM processes in RI processes, obtaining the same limitation. For instance, in [3] these concepts are used in RI on-line control strategies. In this case, the centroid of the flow front nodes is used to compute the optimal vent. The optimal flow front must be vent oriented flow. In this case, after obtaining the centroid of the flow front contour, the Euclidean distance between the real vent, allocated in the mould, and the optimal vent, the centroid, is used as a criterion to correct the flow front advancement in each time instant. This algorithm has limited applications because the vent may not be a point. In addition, this algorithm only can be used for 2D RI moulds due to the Euclidean distance and the centroid does not take into account the complex mould geometry. This level of difficulty increases if the 2.5D real dimensions of the industrial

moulds is considered in the development of these algorithms. To the authors' knowledge, this problem has not been treated in the literature for 2.5D RI processes.
The goal of our research is to propose a tool to define optimal Resin Infusion filling process, where the vents and gate inlets can be curves. For this propose, in this paper is introduced a novel filling process representation that establish a new computational framework extended for LCM processes. It is obtained by the use of a technique called *configuration spaces*. The main property of these spaces is that permits to represent the process to study in terms of process configuration parameters, instead of a customary Cartesian axis. These spaces are commonly used in mobile robots [5], where the configuration parameters are the turning radius, path length, velocity, etc, permitting an easy understanding of the process and a fast algorithm computation. The use of these spaces in LCM processes is called *Flow Pattern Configuration Spaces* (FPCS). As in mobile robots, the configuration parameter selection is free and depends on the configuration space application.

The resulting configuration spaces permits to represent the selected optimal criterion of the filling process in a form where it is easy to validate. The variables used in this work are the common optimal criterions used in the literature. Nevertheless, a major motivation of using these spaces is that it is possible to define mathematically the optimal flow front behaviour using the *homotopy* properties of the curves described by the flow, that is, the flow path that minimizes the required energy of the flow front displacement between the gate and the vent, so as to obtain an optimal filling process. This is the main goal of our research.

The results of this paper are extended to some other possible applications of LCM process design [7]. This paper shows how to use the FPCS to measure the quality of the filling process, optimize LCM processes as well as use this approach in on-line control systems.

FLOW PATTERN TIME SPACES

As can be hereinbefore explained in the introduction, RI processes introduces a new level of difficulty due to the vent and gate inlets are not points, can be lines or curves. To threat this problem efficiently, also for 2.5D real moulds, is proposed the use of a novel technique called *Flow Pattern Configuration Spaces* (FPCS). For the definition of these spaces, it is necessary to choose the configuration parameters. In this sense, one of the parameters commonly used in LCM processes is the filling time. It is well-known that the optimal filling process requires that the flow front achieves the vent at the same time. If the vent line is a curve, the flow front must be achieving the entire vent at the same time so if the filling process is optimal, the last flow front must be coinciding to the vent, and that is, the vent representation must be a straight line. Therefore, the time at which the flow achieves each node is defined the first configuration parameter. The other parameter is the angle defined by a point of interest, that is, the nozzle injection or the vacuum vent at the evaluated point location. The resulting configuration space is called *Flow Pattern Time Space* (FPTS). Therefore, given a simulation result, the configuration parameters are an angle formed between the interest point and each node, θ, and the normalized filling time, $\tau \in [0,1]$. There are two possibilities to represent this configuration space, FPTS-2D and FPTS-1D, in which the flow fronts are translated into exact circles or straight lines respectively. Fig. 2 shows the required computation.

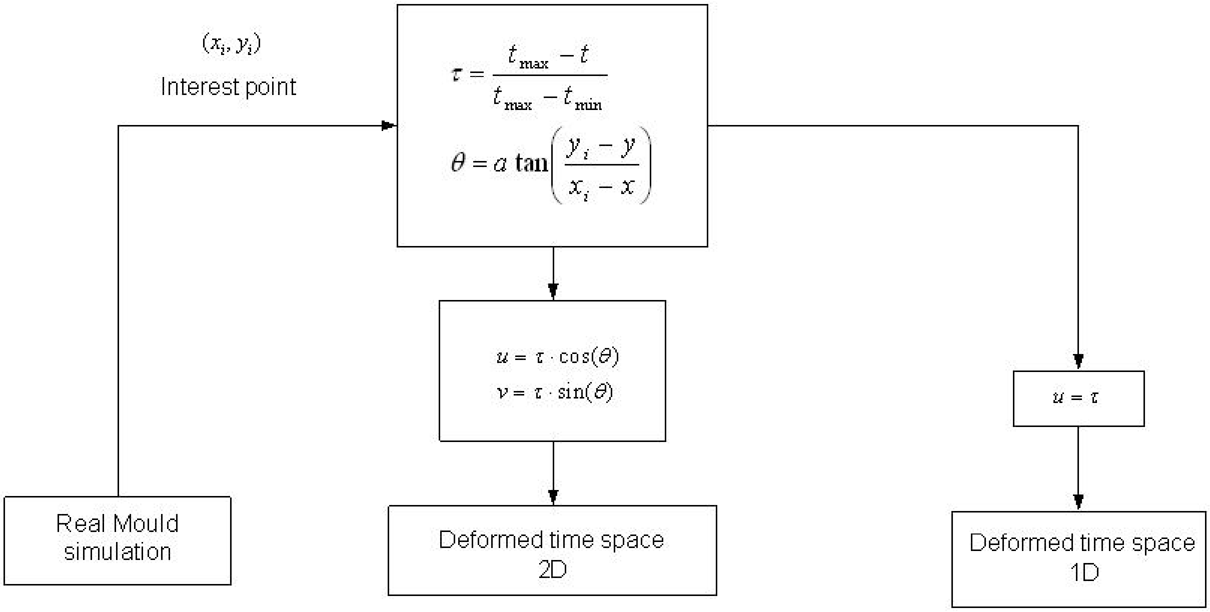


Fig. 2 Variable computation required in FPTS.

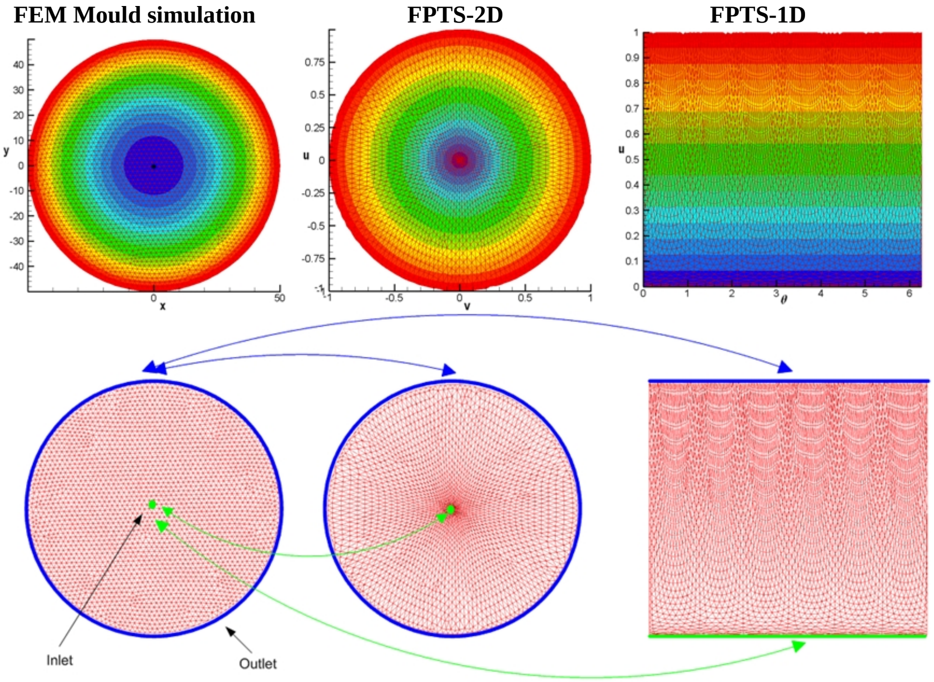
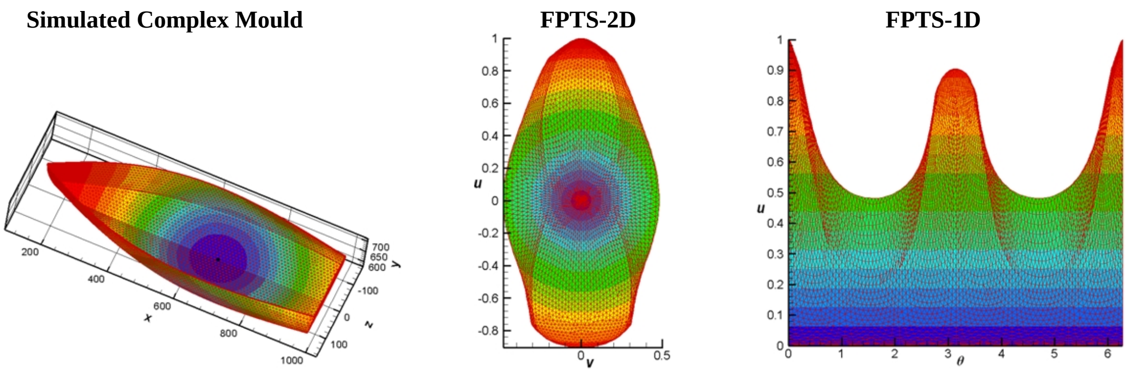
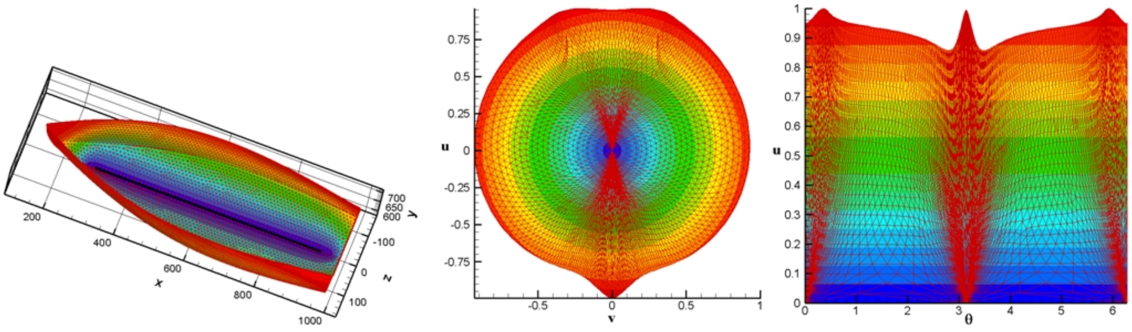


Fig. 3 FPTS (up) and the representation correspondence between them (down).

Fig. 3 (up) shows an example of FPTS where the vent is on the mould perimeter and the gate inlet is located at the circle centre. Fig. 3 (down) shows the correspondence of inlets and outlets in the different FPTS representations. This representation does not depend on the mould dimension and the outlet or inlet shape. Fig. 4 shows some examples of a 2.5D mould with a gate inlet point and a better gate inlet line.



b) 2.5D complex mould with inlet point gate



c) 2.5D complex hull mould with line shaped inlet gate

Fig. 4 Examples of Flow Pattern Time Spaces for 2.5D moulds.

FLOW PATTERN DISTANCE SPACES

In the FPCS defined in the previous section, the selected configuration parameter is the filling time. This variable selection is due to one of the criterion for the optimal filling process is that the flow front achieves the vent at the same time. In the same sense, other criterion used to define the optimal filling processes [1-4] is that the flow front must be vent oriented at each time instant. It implies that the nodes that compose the flow front should be the same distance to the vent. Through this concept, in this section is proposed a FPCS that is based on the distance. This distance is computed to the node mould location and an interest point that, following the ideas of [1-4] must be the vent. The resulting space is called *Flow Pattern Distance Space* (FPDS). The required computation is illustrated in Fig. 5.

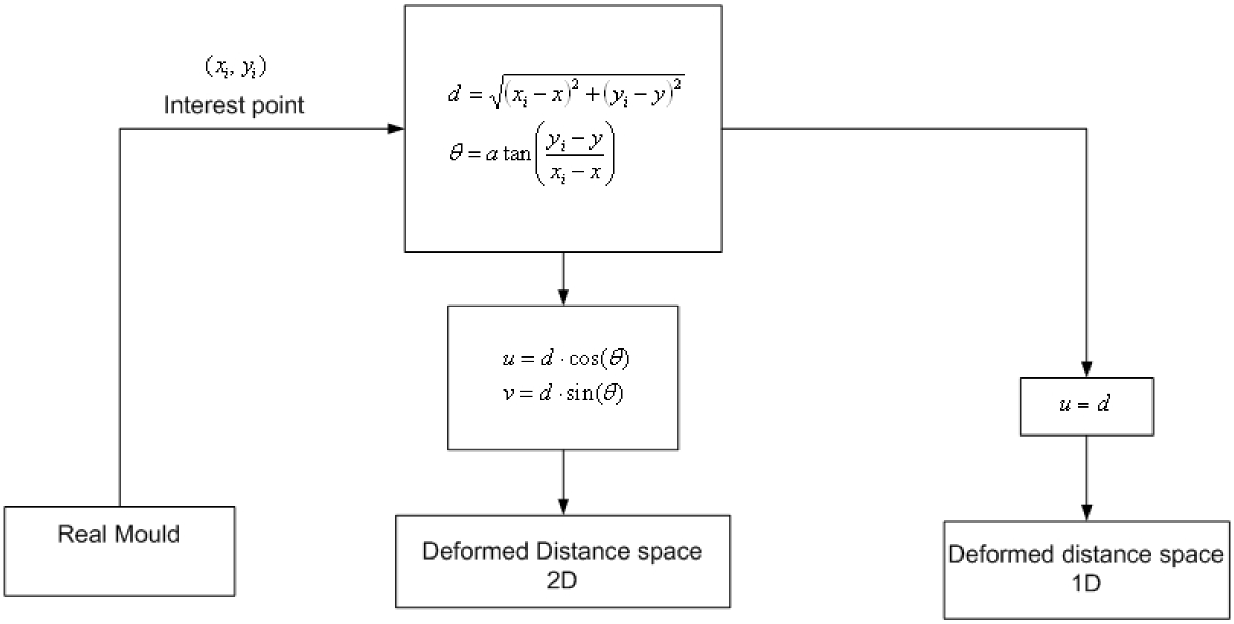


Fig. 5 Variable computation required in FPDS using the Euclidean distance.

For the distance computation, if the Euclidean distance is used, the resulting FPDS is only useful for 2D moulds. In order to extend it to 2.5D, the distance is computed using a cutting plane defined by the interest point and each node, see Fig. 6.

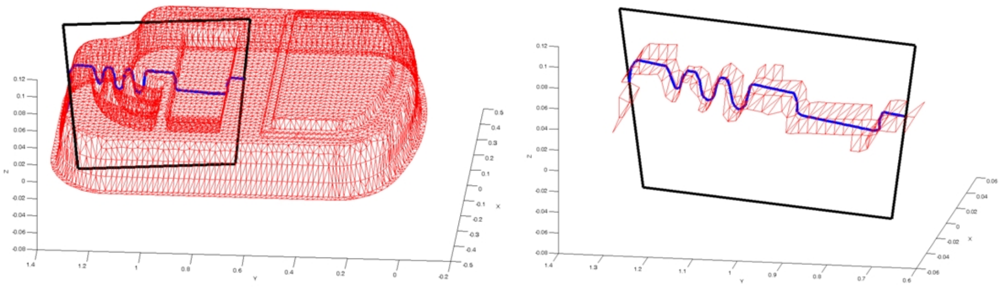
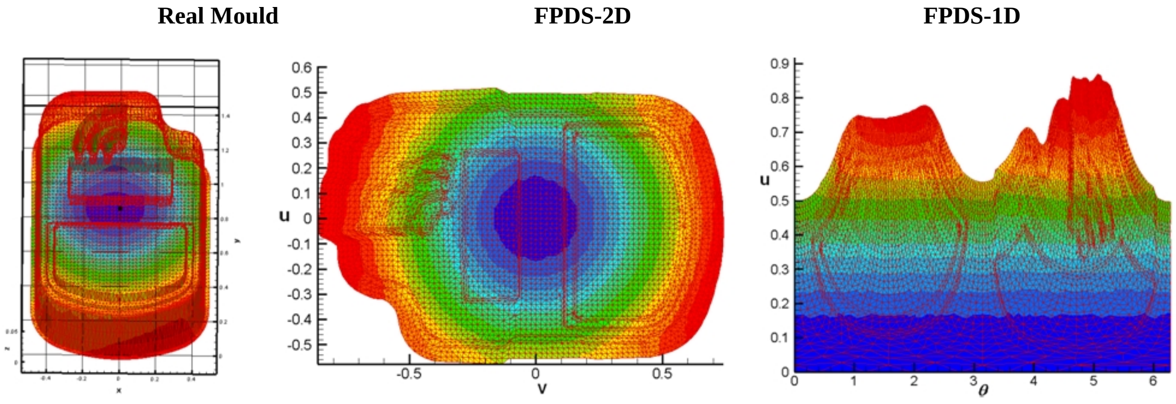


Fig. 6 Distance computation for 2.5D complex moulds.

Fig. 7 shows an example of the FPDS. For the FPDS validation, simulation results are represented using the interest point as a gate inlet. Therefore, the flow fronts must be straight lines and circles if the FPDS accomplish the concept of vent oriented flow front.

The FPDS permits an easy understanding of the vent oriented flow concept used in [1-4] because if it is accomplished, the flow front must be represented in the FPDS as a circle or straight line, FPDS-2D and FPDS-1D, respectively.


Real Mould

FPDS-2D

FPDS-1D

Fig.7 Distance computation for 2.5D complex moulds.

CONCLUSIONS AND FUTURE WORK

In this paper is presented a novel filling process representation tool. It is based on the definition of the coordinate system by means of the process parameters related to the flow, instead of a customary Cartesian coordinate system. This kind of representation is called a Configuration Space and for LCM processes, *Flow Pattern Configuration Spaces* (FPCS). The application of FPCS to LCM processes permits an easy understanding of the filling process for complex 2.5D moulds independently of the vent and gate inlet shape. In this paper two different FPCS are proposed, one based on the filling time, called *Flow Pattern Time Spaces* (FPTS) and the other one on distances, called *Flow Pattern Distance Spaces* (FPDS). The first defines a configuration space where the flow fronts are ever represented as a straight lines or circles. It permits an easy understanding of the filling process because if the flow attains the vent at the same time, the contour of the FPTS representation is a circle or a straight line. The second one called FPDS permits to show easily if the flow front has an optimal orientation to the vent because if this premise is accomplished, the flow front appears as a straight line or a circle.

In the FPCS, an amount of different configuration parameters can be considered, such as incubation time, flow front velocity, etc. It is important to remark that the configuration space is *N* dimensional, implying that more configuration parameters can be used to develop a new FPCS. The investigation of this new configuration spaces and the application that can be do in LCM process are our present work. This paper is extended in [7], where some applications of FPCS in LCM optimization and control are proposed.

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