# A simplified computational treatment for Non-Isotropic Permeability Flow Models based on Flow Pattern Configuration Spaces

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**ABSTRACT**: In this paper we propose a new configuration space, called Flow Pattern Permeability Space (FPkS) that allows us to extend the FPCS methodology previously demonstrated in [1] to non-isotropic media. This space was obtained by applying the standard normalization scheme used in classic formulation of anisotropic Darcy flow where elliptic flow is normalized to a circular flow. Then, it is possible to scale the 2D-FPDS in order to translate the computation of non-isotropic model into an isotropic model. Therefore, it allows using the methodology proposed in our previous work, [7] for the channel distribution design for non-isotropic models. At the end of the paper some simulation results are shown.

**KEYWORDS**: Configuration Spaces, non-isotropic models, LCM processes.

## INTRODUCTION

Resin Infusion (RI) processes are one of the common techniques used in the industry for large composite parts production. This technique uses vacuum pressure to drive the resin into a laminate. Preform is laid dry into the mould and the vacuum is applied before the resin is introduced. Once a complete vacuum is achieved, resin is sucked into the laminate via placed tubing. Negative pressure allows the top half of the mould to be made of a flexible material where resin channel networks can be introduced to improve the filling process. These channel networks can be taking whatever form, introducing a new degree of freedom in the RI process design, which is not available in other LCM processes like RTM where the inlet/outlets are discrete points. The inlet/outlet location is one of the most critical tasks in the design of LCM processes. For this reason, there are an amount of algorithms in the literature that treats to find the optimal location.
In general, the common algorithm used in the literature to solve the optimal inlet/outlet location is a FEM simulation coupled with a genetic algorithm or improvements of each of them, see for instance [2]-[5]. In these cases, search algorithms work in Cartesian space, generating elevated computational costs. In fact, the algorithm proposed in the literature is the best alternative if the problem is analyzed from the Cartesian space. Genetic Algorithms are one of the best options to find local minima in a large search spaces. The computational

inefficiency of this algorithms is not caused because of genetic algorithm or FEM simulation, is caused because of Cartesian Space is not the most beneficial representation form of the LCM process variables to optimize.

## PREVIOUS DEFINITIONS: FLOW PATTERN DISTANCE SPACES

All the moulds used in LCM processes are limited for the mould contour. Therefore, the mould can be defined as a region $\Omega \subset \Re^3$ closed and connected. If we suppose that the mould perimeter ( $\partial\Omega$ ) can be parameterized through a closed curve $\gamma^*(u) = (x(u), y(u), z(u))$ where $u \in [0,1]$ and $\gamma^*(0) = \gamma^*(1)$ , accomplishing that $u, v \in (0,1)$, if $\gamma^*(u) = \gamma^*(v)$ then $u = v$. The mould filling can be defined as a curve $\gamma : (0,T] \rightarrow C_{0,1}([0,1], \Omega]$ where the space $C_{0,1}([0,1], \Omega)$ is composed by the injective applications for the interval $[0,1]$ in the mould $\Omega$.
In each time instant, $t \in [0,T]$, the curve $\gamma_t$ represents the flow front where $\gamma_T = \gamma^*$ representing that for $t = T$ the mould $\Omega$ is completely filled and;

$$\lim_{t \to 0} \gamma_t = \gamma_0 , \quad \lim_{t \to T} \gamma_t = \partial\Omega$$

where $\gamma_0(u) = (x^*, y^*, z^*)$ is a constant curve called the inlet. In RTM process, this curve is a point, $\gamma_0(u) = (x^*, y^*, z^*) \forall u \in [0,1]$ but in RI process, $\gamma_0(u) = (x^*(u), y^*(u), z^*(u)) \forall u \in [0,1]$,

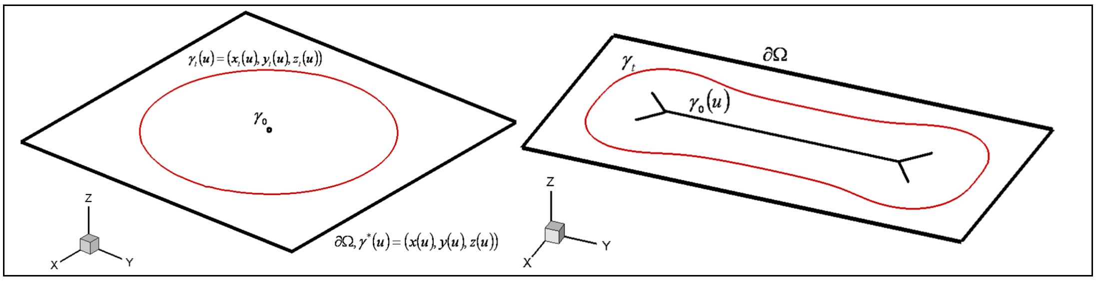

Fig. 1 Topology of LCM processes, left process, RTM and right process, RI.

Form this definition we can see that in whatever LCM process, $\gamma_t(u) \subset \gamma_0(u)$, that is, the flow front, $\gamma_t(u)$ , ever contains the inlet, $\gamma_0(u)$. It implies that it is possible to change the intrinsic variable as;

$$\gamma_t(u) \rightarrow \gamma_t(\theta(u)) \quad \text{where} \quad \theta(u) = a\tan\left(\frac{y_t(u)}{x_t(u)}\right)$$

If the mould geometry is defined in $\Re^3$ , this angle is computed through the projection of the curve $\gamma_t(u)$ in $\Re^2$. If $\gamma_0(u)$ is not a point, $\theta(u)$ is computed through the predefined point of the curve $\gamma_0(w), w \in [0,1]$. This change of variable is not an arbitrary decision, is due to the flow is radial from $\gamma_0(u)$, whether a point as if a curve.
Based on this definition, one of the FPCS proposed in [1] was based on the node-to-node distance criterion. If the mould is defined in a $\Re^2$ space and $\gamma_0(u)$, the

inlet, is a point, the distance is computed using the Euclidean distance as $\mathbf{\Psi}(u)=d(\boldsymbol{\gamma}_t(u),\boldsymbol{\gamma}_0(u))=\|\boldsymbol{\gamma}_t(u),\boldsymbol{\gamma}_0(u)\|_2$. If the mould is defined in $\Re^3$, geodesic distance is used, see [1], and defined as; $\mathbf{\Psi}(u)=g(\boldsymbol{\gamma}_t(u),\boldsymbol{\gamma}_0(u))$. If $\boldsymbol{\gamma}_0(u)$, is not a point as is the case of resin infusion process, in $\Re^2$ is used the minimum distance; $Min\{d(\boldsymbol{\gamma}_t(u),\boldsymbol{\gamma}_0(u))\forall u\in[0,1]\}$, meanwhile if the mould is defined in $\Re^3$; $Min\{g(\boldsymbol{\gamma}_t(u),\boldsymbol{\gamma}_0(w))\forall w\in[0,1]\}$, see Fig 2 (left).

The resulting spaces have been so-called, "*Flow Pattern Distance Spaces*" (FPDS). A polar space representation is so-called 1D-FPDS. For moulds defined in $\Re^3$, or when $\boldsymbol{\gamma}_0(u)$ is not a point, it is developed another space in $\Re^2$ so-called 2D-FPDS. This space is computed as $u=\{d,g\}\cdot\cos(\theta)$, $v=\{d,g\}\cdot\sin(\theta)$, where *u* and *v* are the coordinates in the new space, see our previous work [1].

## THE USE OF FPDS FOR THE CHANNEL DISTRIBUTION DESIGN

One of the main properties of the resulting spaces, 2D-FPDS and 1D-FPDS is that are node to node connected to the original Cartesian space where the original mould is defined; making reversible the transformation, see [1]. This fact allows computing optimization algorithms in these spaces and translating the results to the Cartesian space.

In [7] it is proposed a simplified based experience formalization of the channel distribution design using the FPDS and Delaunay triangulation to avoid any iterative algorithm. Delaunay triangulation, is deduced by the Process Performance Index proposed in, [7] and [8]. In these works, flow front distance to the vent was used to measure how suitable the shape of the flow front is in each time instant. This implies that, if we consider $\boldsymbol{\gamma}_{t=0}(u)=\boldsymbol{\gamma}_0(u)$, the injector must also be at the same distance with respect to vent. If this concept is focused on infusion processes, both the optimal shape and its location in the mould must fulfill this premise with respect to the vent, allocated in the mould contour to homogenize local pressure distribution in the mould. Under this assumption, the problem of obtaining the best distribution channel becomes a geometric problem that can be easily solved by Delaunay triangulation. In Fig. 2 (right) is shown an example result at different Delaunay resolution for a mould like a boat.

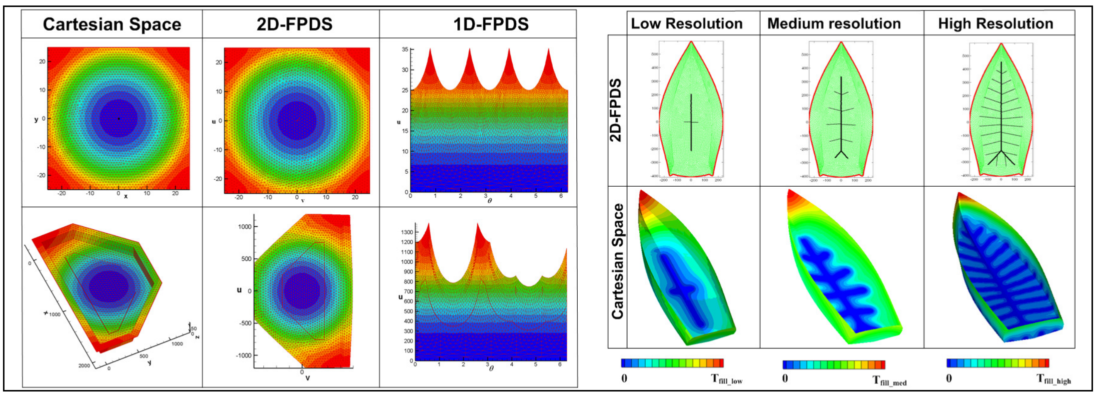


Fig. 2 Examples of FPDS (left). Channel distribution examples (right).

## FLOW PATTERN PERMEABILITY SPACES

The algorithm proposed in [7] joined with the FPDS allows to compute the idoneous distribution channel in seconds but is only useful for isotropic models. In order to generalize this algorithm, it is necessary to generate a new configuration space, so-called "*Flow Pattern Permeability Spaces*" (FPkS). This space was obtained by applying the standard normalization scheme used in classic formulation of anisotropic Darcy flow [6] where elliptic flow is normalized to a circular flow by scaling of $\hat{u}_{11}$ and $\hat{u}_{22}$ in:

$$\frac{\hat{u}_{11}}{\hat{u}_{22}} = \sqrt{\frac{K_{11}}{K_{22}}}$$

Where $\hat{u}_{11}$ and $\hat{u}_{22}$ are the principal elliptical parameters that defines the flow front shape in this cases. Through equation (1), it is possible to scale the FPDS in order to translate the non-isotropic model into an isotropic model just only using the next polar scaling factor;

$$\rho(\theta) = \frac{1}{\sqrt{\frac{\cos(\theta+\beta)^2}{(R\cdot\hat{u}_{11})^2} + \frac{\sin(\theta+\beta)^2}{(R\cdot\hat{u}_{22})^2}}} \qquad R^2 = \frac{K_{11}}{\hat{u}_{11}} = \frac{K_{22}}{\hat{u}_{22}}$$

where $\beta$ is the angle inclination for the permeability axis. Through this definition, FPkS is formulated like a FPDS just only introducing this scaling factor as; $\mathbf{\Psi}(u,\theta) = \rho(\theta)\cdot\{d(\theta), g(\theta)\}$ and for 2D-FPkS; $u = \rho(\theta)\cdot\{d, g\}\cdot\cos(\theta)$, $v = \rho(\theta)\cdot\{d, g\}\cdot\sin(\theta)$. Fig.3 shows some FPkS examples and Fig.4 shows two simple examples to compare channel distribution solutions in each case.

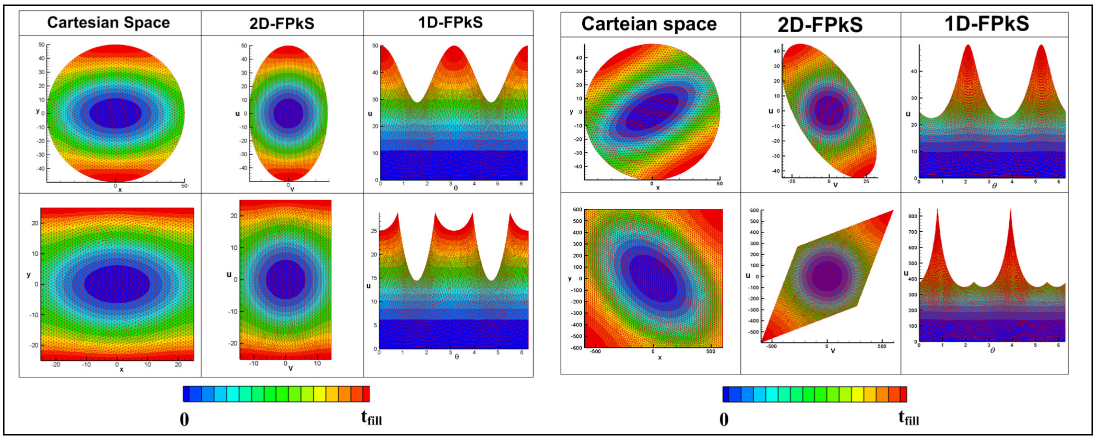


Fig. 3 Flow Pattern Permeability Spaces (FPkS).

## CONCLUSIONS

In this paper we propose a new configuration space, so-called "*Flow Pattern Permeability Spaces*" (FPkS), that allows us to extend the FPCS methodology previously demonstrated in [1] to non-isotropic media. Through this space, it is possible to use the methodology for the channel distribution design proposed in our previous work, [7] for non-isotropic models.

The present study does not take into account the fabric deformation, see [9]. This task, as well as a methodology to measure this deformation previously to allocate the channel distribution in the mould by means artificial vision techniques, is our immediately future works.

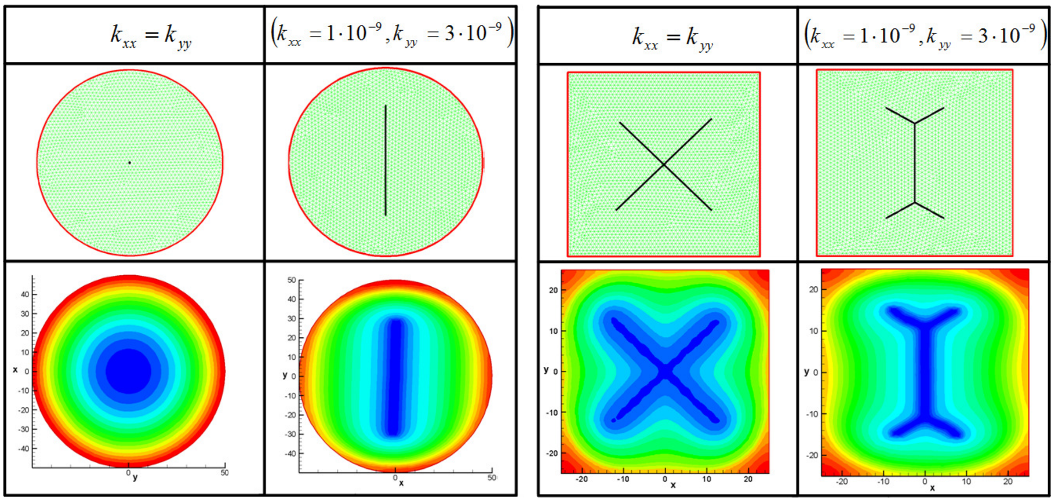


Fig. 4 Channel distribution comparisons for isotropic and non-isotropic models.

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