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Vorwort

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Berichterstattung heißt hier Dokumentation des Transfers aktueller Ergebnisse aus mathematischer Forschungs- und Entwicklungsarbeit in industrielle Anwendungen und Softwareprodukte – und umgekehrt, denn Probleme der Praxis generieren neue interessante mathematische Fragestellungen.

Prof. Dr. Dieter Prätzel-Wolters
Institutsleiter

Kaiserslautern, im Juni 2001

A 3D MODEL FOR FIBER LAY-DOWN IN NONWOVEN PRODUCTION PROCESSES

A. KLAR †‡, J. MARINGER ‡, AND R. WEGENER‡

Abstract. In this paper a three dimensional stochastic model for the lay-down of fibers on a moving conveyor belt in the production process of nonwoven materials is derived. The model is based on stochastic differential equations describing the resulting position of the fiber on the belt under the influence of turbulent air flows. The model presented here is an extension of an existing surrogate model, see [6, 3].

Key words. fiber dynamics, Fokker-Planck equations, diffusion limits

AMS subject classifications. 37H10, 60H30, 41A60, 65C05

1. Introduction. Nonwoven materials are produced in melt-spinning operations: hundreds of individual endless fibers are obtained by the continuous extrusion of a molten polymer through narrow nozzles that are densely and equidistantly placed in a row at a spinning beam. The viscous / viscoelastic fibers are stretched and spun until they solidify due to cooling air streams. Before the elastic fibers lay down on a moving conveyor belt to form a web, they become entangled and form loops due to the highly turbulent air flows. In [12] a general mathematical model for the fiber dynamics is presented which enables the full simulation of the process. Due to the huge amount of physical details these simulations of the fiber spinning and lay-down usually require an extremely large computational effort and high memory storage, see [13]. Thus, a simplified two-dimensional stochastic model for the fiber lay-down process is introduced in [6]. This model describes the position of the fiber on the transport belt by a stochastic differential system containing parameters that characterize the process. These parameters have to be identified from a few representative fibers simulated by the detailed model. Then, the surrogate model can be used to calculate fast and efficiently the behavior of hundreds of long fibers for fleece production. In [6, 7] an analytic investigation of the corresponding Fokker-Planck equation has been performed, asymptotic properties and ergodicity of the process have been proven and explicit rates for the convergence to the stationary solution have been obtained.

In the present paper the above 2D model is extended to three dimensions. This is crucial, if one wants to describe further properties of the resulting web, like permeability. In a first step we revisit the 2D model and rewrite it in a coordinate free form, see section 2. In section 3 an isotropic 3D model is obtained by a suitable transformation of the deterministic and stochastic processes. Since the resulting fleece is usually rather thin and has an anisotropic orientation of the fibers, we modify the isotropic 3D model accordingly, see section 4. Further, we investigate the connections between the models by looking at the associated Fokker-Planck equations and their limiting behavior. The limit of large turbulence is considered in section 5, as well as a large coiling force limit. Finally, we show numerical results and state a possible strategy for parameter estimation of the modified 3D model in section 6.

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2. Revisiting the 2D Model. Consider a slender, elastic, non-extensible and endless fiber in a lay-down regime. Let the fiber be produced with a certain spinning speed, excited into motion by a surrounding highly turbulent air flow and laid down on a conveyor belt which is for the time being assumed to be non-moving. For the case of a moving belt see Remark 1. Due to its slenderness, the fiber on the two-dimensional transport belt is modeled as an arc-length parametrized curve $\boldsymbol{\xi} : \mathbb{R}_0^+ \to \mathbb{R}^2$, defined by the solution of a dynamical system for $\boldsymbol{\xi}_t$ with the arc-length t. This dynamical system is given by the following stochastic differential equations, see [6]

$$\begin{aligned} d\boldsymbol{\xi}_t &= \boldsymbol{\tau}(\alpha_t)\, dt \\ d\alpha_t &= -\nabla V(\boldsymbol{\xi}_t) \cdot \boldsymbol{\tau}^{\perp}(\alpha_t)\, dt + A\, dW_t \ , \end{aligned} \tag{2.1}$$

equipped with appropriate initial conditions $\boldsymbol{\xi}_0, \alpha_0$. The normalized tangent is $\boldsymbol{\tau}(\alpha) = (\cos\alpha, \sin\alpha)^T$. Introducing the corresponding orthonormal polar unit vector $\boldsymbol{\tau}(\alpha)^{\perp} = (-\sin\alpha, \cos\alpha)^T$, the deterministic drift term in the second equation ensures that the fiber tends back to the origin as a consequence of the coiling behavior of the fiber. The throwing ranges of the fiber can be controlled with help of the potential V. One may, for example, choose $V(\boldsymbol{\xi}) = (\xi_1^2/\sigma_1^2 + \xi_2^2/\sigma_2^2)/2$ with the throwing ranges σ_1 and σ_2, see Remark 2. All stochastic effects occurring in the production process are summarized in the one-dimensional Wiener process $(W_t)_{t\geq 0}$ with diffusion constant A. This model is refered to as the *original 2D model*.

We rewrite (2.1) in a coordinate free form using Ito's or Stratonovich's calculus, respectively,

$$\begin{aligned} d\boldsymbol{\xi}_t &= \boldsymbol{\tau}_t\, dt \\ d\boldsymbol{\tau}_t &= -\big(\nabla V(\boldsymbol{\xi}_t) \cdot \boldsymbol{\tau}_t^{\perp}\big)\boldsymbol{\tau}_t^{\perp}\, dt - \frac{1}{2}A^2 \boldsymbol{\tau}_t\, dt + \boldsymbol{\tau}_t^{\perp} A\, dW_t \\ &= -\big(\nabla V(\boldsymbol{\xi}_t) \cdot \boldsymbol{\tau}_t^{\perp}\big)\boldsymbol{\tau}_t^{\perp}\, dt + \boldsymbol{\tau}_t^{\perp} \circ A\, dW_t \\ \|\boldsymbol{\tau}_t\| &= 1 \end{aligned}$$

or in more compact form

$$\begin{aligned} d\boldsymbol{\xi}_t &= \boldsymbol{\tau}_t\, dt \\ d\boldsymbol{\tau}_t &= \big(I - \boldsymbol{\tau}_t \otimes \boldsymbol{\tau}_t\big)\big(-\nabla V(\boldsymbol{\xi}_t)\, dt + A\, d\boldsymbol{W}_t\big) - \frac{1}{2}A^2 \boldsymbol{\tau}_t\, dt \\ &= \big(I - \boldsymbol{\tau}_t \otimes \boldsymbol{\tau}_t\big) \circ \big(-\nabla V(\boldsymbol{\xi}_t)\, dt + A\, d\boldsymbol{W}_t\big) \\ \|\boldsymbol{\tau}_t\| &= 1 \ . \end{aligned} \tag{2.2}$$

Thereby, I denotes the identity matrix, $\circ$ denotes the usage of Stratonovich integrals and $(\boldsymbol{W}_t)_{t\geq 0}$ is a two-dimensional Wiener process. The algebraic constraint takes into account the arc-length parametrization for the inextensible fibers. We note that the stochastic part in (2.2) is a Brownian motion on the unit circle, see for example [14].

REMARK 1. *Let the fiber be produced with the spinning speed v_{spin} and laid down on a conveyor belt moving with the velocity v_{belt}. The fiber curve is now denoted as $\boldsymbol{\eta} : \mathbb{R}_0^+ \to \mathbb{R}^2$. The arc-length parametrization and in-extensibility gives again*

$$d\boldsymbol{\eta}_t = \begin{pmatrix} \cos\alpha_t \\ \sin\alpha_t \end{pmatrix} dt \ ,$$

where α denotes the angle of the fiber relative to the direction of motion $\boldsymbol{e}_1$ of the transport belt. The reference point of the spinning process determined by the position of the nozzle moves in the coordinate system of the transport belt in the direction $-\boldsymbol{e}_1$. Thus,

$$\boldsymbol{\xi}(t) = \boldsymbol{\eta}(t) - (-\kappa t \boldsymbol{e}_1)$$

describes the deviation of the fiber from the reference point as a function of the arc-length parameter t, where $\kappa = v_{belt}/v_{spin} \in [0,1]$ is the ratio between the belt and spinning speeds. Following [6], we model $(\boldsymbol{\xi},\alpha)$ by the stochastic differential system

$$\begin{aligned} d\boldsymbol{\xi}_t &= \boldsymbol{\tau}(\alpha_t)\,dt + \kappa \boldsymbol{e}_1 dt \\ d\alpha_t &= -\nabla V(\boldsymbol{\xi}_t) \cdot \boldsymbol{\tau}_t^{\perp} dt + A\,dW_t \ . \end{aligned} \tag{2.3}$$

We might generalize the last model with help of the concept of reference curves allowing the consideration of further specific production processes, see [10]. Introducing a reference curve $\boldsymbol{\gamma}$ the generalized model reads

$$\begin{aligned} d\boldsymbol{\xi}_t &= \boldsymbol{\tau}(\alpha_t)\,dt + d\boldsymbol{\gamma}_t \\ d\alpha_t &= -\nabla V(\boldsymbol{\xi}_t) \cdot \boldsymbol{\tau}_t^{\perp} dt + A\,dW_t \ . \end{aligned} \tag{2.4}$$

REMARK 2. *The Fokker-Planck equation associated to (2.1) reads*

$$\partial_t P = -\boldsymbol{\tau} \cdot \nabla_\xi P + \nabla V(\boldsymbol{\xi}) \cdot \partial_\alpha(\boldsymbol{\tau}^\perp P) + \frac{1}{2} A^2 \partial_{\alpha\alpha} P \tag{2.5}$$

and the stationary density is given by

$$P_{stat}(\boldsymbol{\xi}) = C \exp(-V(\boldsymbol{\xi}))\ , \tag{2.6}$$

where C is a normalization constant. Using the potential $V(\boldsymbol{\xi}) = (\xi_1^2/\sigma_1^2 + \xi_2^2/\sigma_2^2)/2$ the throwing ranges σ_1, σ_2 are interpreted as standard deviations σ_1, σ_2 of the normal distribution.

REMARK 3. *The limit for large values of the diffusion coefficient A is*

$$d\boldsymbol{\xi}_t = -\frac{1}{A^2} \nabla V(\boldsymbol{\xi}_t)\,dt + \sqrt{2}\frac{1}{A}\,d\boldsymbol{W}_t\ , \tag{2.7}$$

see [3]. It will be called the reduced 2D model in the following.

3. The Isotropic 3D Model. In this and the following section the above described two-dimensional model will be extended to three dimensions. Again, we model the motion of the fiber as an arc-length parametrized curve $\boldsymbol{\xi} : \mathbb{R}_0^+ \to \mathbb{R}^3$ with normalized tangent $\boldsymbol{\tau}$, which is in spherical coordinates given by

$$\boldsymbol{\tau}(\alpha,\theta) = \begin{pmatrix} \cos\alpha \sin\theta \\ \sin\alpha\sin\theta \\ \cos\theta \end{pmatrix} \ .$$

We introduce the orthonormal spherical unit vectors

$$\boldsymbol{n}_1(\alpha) = \begin{pmatrix} -\sin\alpha \\ \cos\alpha \\ 0 \end{pmatrix}, \quad \boldsymbol{n}_2(\alpha,\theta) = \begin{pmatrix} \cos\alpha\cos\theta \\ \sin\alpha\cos\theta \\ -\sin\theta \end{pmatrix}$$

and follow the procedure for the 2D case to get the stochastic differential equations in local coordinates in the 3D case. We start by translating the Stratonovich coordinate free formulation (2.2) to three dimensions introducing an additional factor $\frac{1}{2}$:

$$\begin{aligned} d\boldsymbol{\xi}_t &= \boldsymbol{\tau}_t\,dt \\ d\boldsymbol{\tau}_t &= \big(I - \boldsymbol{\tau}_t \otimes \boldsymbol{\tau}_t\big) \circ \big(-\frac{1}{2}\nabla V(\boldsymbol{\xi}_t)\,dt + A\,d\boldsymbol{W}_t\big) \\ \|\boldsymbol{\tau}_t\| &= 1\ . \end{aligned} \tag{3.1}$$

Considering the deterministic part separately gives

$$\begin{aligned} d\boldsymbol{\tau}_t &= -\frac{1}{2}\big(I - \boldsymbol{\tau}_t \otimes \boldsymbol{\tau}_t\big)\nabla V(\boldsymbol{\xi}_t)\,dt \\ &= -\frac{1}{2}\big(\boldsymbol{n}_{1t} \otimes \boldsymbol{n}_{1t} + \boldsymbol{n}_{2t} \otimes \boldsymbol{n}_{2t}\big)\nabla V(\boldsymbol{\xi}_t)\,dt \\ &= -\frac{1}{2}\big(\nabla V(\boldsymbol{\xi}_t)\cdot \boldsymbol{n}_{1t}\big)\boldsymbol{n}_{1t}\,dt - \frac{1}{2}\big(\nabla V(\boldsymbol{\xi}_t)\cdot \boldsymbol{n}_{2t}\big)\boldsymbol{n}_{2t}\,dt\ . \end{aligned} \tag{3.2}$$

Applying the chain rule ($\boldsymbol{\tau} = \boldsymbol{\tau}(\alpha,\theta)$) and comparison of coefficients leads to the deterministic equations in local coordinates

$$\begin{aligned} \sin\theta_t d\alpha_t &= -\frac{1}{2}\nabla V(\boldsymbol{\xi}_t)\cdot \boldsymbol{n}_1(\alpha_t)\,dt \\ d\theta_t &= -\frac{1}{2}\nabla V(\boldsymbol{\xi}_t)\cdot \boldsymbol{n}_2(\alpha_t,\theta_t)\,dt\ . \end{aligned}$$

Next, we rewrite the stochastic part in Ito's formulation and compute

$$\begin{aligned} d\boldsymbol{\tau}_t &= \big(I - \boldsymbol{\tau}_t \otimes \boldsymbol{\tau}_t\big)A\,d\boldsymbol{W}_t - A^2\boldsymbol{\tau}_t\,dt \\ &= \big(\boldsymbol{n}_{1t} \otimes \boldsymbol{n}_{1t} + \boldsymbol{n}_{2t} \otimes \boldsymbol{n}_{2t}\big)A\,d\boldsymbol{W}_t - A^2\boldsymbol{\tau}_t\,dt \\ &= \boldsymbol{n}_{1t}A\,dW_t^{(1)} + \boldsymbol{n}_{2t}A\,dW_t^{(2)} - A^2\boldsymbol{\tau}_t\,dt\ , \end{aligned} \tag{3.3}$$

which is a Brownian motion on the unit sphere, see [14] or [15]. $(W_t^{(1)})_{t\geq 0}$ and $(W_t^{(2)})_{t\geq 0}$ are one-dimensional Wiener processes.

Using Ito's formula for $\boldsymbol{\tau}(\alpha,\theta)$ the stochastic part in local coordinates is given by

$$\begin{aligned} \sin\theta_t d\alpha_t &= A\,dW_t^{(1)} \\ d\theta_t &= \frac{1}{2}A^2\cot\theta_t\,dt + A\,dW_t^{(2)}. \end{aligned}$$

Alltogether the three dimensional model equations in spherical polar coordinates are

$$\begin{aligned} d\boldsymbol{\xi}_t &= \boldsymbol{\tau}(\alpha_t,\theta_t)\,dt \\ \sin\theta_t d\alpha_t &= -\frac{1}{2}\nabla V(\boldsymbol{\xi}_t)\cdot \boldsymbol{n}_1(\alpha_t)\,dt + A\,dW_t^{(1)} \\ d\theta_t &= -\frac{1}{2}\nabla V(\boldsymbol{\xi}_t)\cdot \boldsymbol{n}_2(\alpha_t,\theta_t)\,dt + \frac{1}{2}A^2\cot\theta_t\,dt + A\,dW_t^{(2)}\ . \end{aligned} \tag{3.4}$$

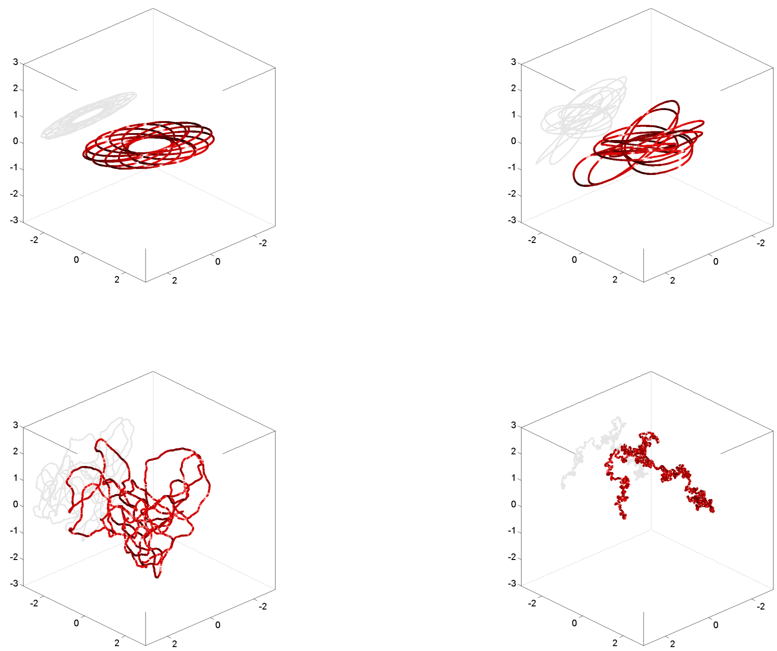

Fig. 3.1: *Influence of noise on fiber trajectories. From left to right, top to bottom* $A = 0$; 0.1; 1; 5.

In the following we refer to this system as the *isotropic 3D model*. Choosing a symmetric potential $V = V(|\boldsymbol{\xi}|)$ the model is invariant under rotations.
Representative fiber scenarios for varying noise amplitude A are illustrated in Figure 3.1 computed by (3.4) after nondimensionalization using an isotropic potential $V(\boldsymbol{\xi}) = |\boldsymbol{\xi}|^2/2$.

However in typical fiber lay-down processes the resulting nonwoven have usually an anisotropic orientation of the fibers as consequence of physical properties and limitations given for example by the impenetrable conveyor belt. For example, the orientation of most of the fibers will concentrate in a direction parallel to the belt. Thus, it is necessary to modify the model such that the orientation of the fibers can be controlled and adapted to measurements. This will be done in the next section.

REMARK 4. *The generalization of the model using arbitrary reference curves* γ *is obviously*

$$\begin{aligned} d\boldsymbol{\xi}_t &= \boldsymbol{\tau}(\alpha_t, \theta_t)\, dt + d\boldsymbol{\gamma}_t \\ \sin\theta_t d\alpha_t &= -\frac{1}{2}\nabla V(\boldsymbol{\xi}_t) \cdot \boldsymbol{n}_1(\alpha_t)\, dt + A\, dW_t^{(1)} \\ d\theta_t &= -\frac{1}{2}\nabla V(\boldsymbol{\xi}_t) \cdot \boldsymbol{n}_2(\alpha_t, \theta_t)\, dt + \frac{1}{2}A^2 \cot\theta_t\, dt + A\, dW_t^{(2)}\ . \end{aligned} \tag{3.5}$$

Remark 5. *The Fokker-Planck equation associated to the isotropic model with non-moving belt is*

$$\partial_t P = -\boldsymbol{\tau}\cdot\nabla_\xi P + \frac{1}{\sin\theta}\frac{1}{2}\nabla V(\boldsymbol{\xi})\cdot\partial_\alpha(\boldsymbol{n}_1 P) + \frac{1}{2}\nabla V(\boldsymbol{\xi})\cdot\partial_\theta(\boldsymbol{n}_2 P)$$
$$-\frac{1}{2}A^2\partial_\theta(\cot\theta P) + \frac{1}{2}\frac{A^2}{\sin^2\theta}\partial_{\alpha\alpha}P + \frac{1}{2}A^2\partial_{\theta\theta}P \tag{3.6}$$

and the stationary density is given by

$$P_{stat}(\boldsymbol{\xi},\theta) = C\sin\theta\exp(-V(\boldsymbol{\xi}))\ . \tag{3.7}$$

4. The Modified 3D Model. The idea of the modified model is that by introducing an additional parameter B we obtain a 3D model which can be adapted to the distributions of the θ-angle in a realistic fleece. With the help of this parameter we are able to weight the directions of the spherical unit-vectors $\boldsymbol{n}_1$ and $\boldsymbol{n}_2$ differently, such that it is possible to capture the anisotropic orientation of the fibers. We suppose that the belt lies in the $(\boldsymbol{e}_1,\boldsymbol{e}_2)$-plane and that the spherical coordinates are determined in a standard way, that means θ is the angle between the direction $\boldsymbol{e}_3$ and the tangent τ on the fiber, whereas α is the angle between the direction $\boldsymbol{e}_1$ and the projection of τ on the reference plane.

Let $B\in[0,1]$, then we replace in (3.2) the factor $\frac{1}{2}$ as follows

$$d\boldsymbol{\tau}_t = -\frac{1}{B+1}\Big(\big(\nabla V(\boldsymbol{\xi}_t)\cdot\boldsymbol{n}_{1t}\big)\boldsymbol{n}_{1t} + B\big(\nabla V(\boldsymbol{\xi}_t)\cdot\boldsymbol{n}_{2t}\big)\boldsymbol{n}_{2t}\Big)\,dt\ . \tag{4.1}$$

We note, that if $B=0$ then we recover the deterministic part in the 2D case observing that $\boldsymbol{n}_1$ is the 3D analogue of $\boldsymbol{\tau}^\perp$. If $B=1$ the isotropic 3-D model is recovered. Furthermore, we change the stochastic part (3.3) redefining

$$d\boldsymbol{\tau}_t = \boldsymbol{n}_{1t}A\,dW_t^{(1)} + \sqrt{B}\boldsymbol{n}_{2t}A\,dW_t^{(2)} - \frac{1}{2}(1+B)A^2\boldsymbol{\tau}_t\,dt\ . \tag{4.2}$$

This ensures again, that for $B=0$ we are back to the 2D case and for $B=1$ to the isotropic 3D case. The modified 3D model ranges between the isotropic 3D model and the 2D model describing fibers with an orientation ranging between a random orientation and an orientation in the $(\boldsymbol{e}_1,\boldsymbol{e}_2)$-plane. Using Ito's formula, we obtain the modified 3D model in local coordinates

$$\begin{aligned} d\boldsymbol{\xi}_t &= \boldsymbol{\tau}(\alpha_t,\theta_t)\,dt\\ \sin\theta_t d\alpha_t &= -\frac{1}{B+1}\nabla V(\boldsymbol{\xi}_t)\cdot\boldsymbol{n}_1(\alpha_t)\,dt + A\,dW_t^{(1)}\\ d\theta_t &= -\frac{B}{B+1}\nabla V(\boldsymbol{\xi}_t)\cdot\boldsymbol{n}_2(\alpha_t,\theta_t)\,dt + \frac{1}{2}A^2\cot\theta_t\,dt + \sqrt{B}A\,dW_t^{(2)}\ . \end{aligned} \tag{4.3}$$

The effect of varying parameter B in (4.3) for an isotropic potential $V(\boldsymbol{\xi}) = |\boldsymbol{\xi}|^2/2$ is shown in Figure 4.1. The noise amplitude is chosen as $A=1$. One observes that for decreasing B the orientation of the fibers is getting more anisotropic. This corresponds to a distribution of the angle θ concentrating around $\theta=\pi/2$.

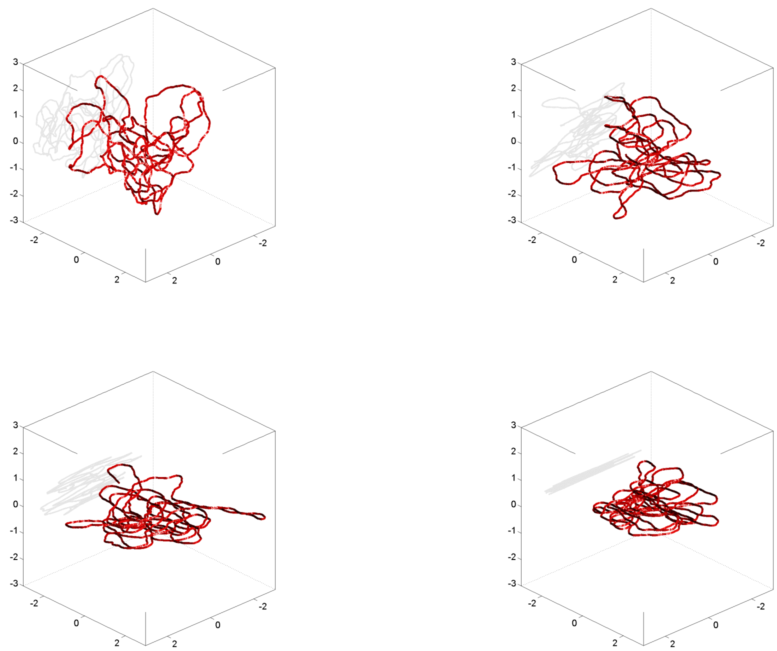

Fig. 4.1: *Influence of the parameter B on fiber trajectories. From left to right, top to bottom $B = 1$; 0.1; 0.01; 0.0001.*

5. Asymptotic Limits and Connections between the Models. In the previous chapters we have distinguished between the 2D model (2.1), the isotropic 3D model (3.4) and the modified 3D model (4.3). In the following we consider the modified 3D model for different limits of the parameters B and A.

5.1. Small and Large B Limit. We investigate the Fokker-Planck equation associated to (4.3)

$$\partial_t P = -\boldsymbol{\tau} \cdot \nabla_\xi P + \frac{1}{\sin\theta} \frac{1}{B+1} \nabla V(\boldsymbol{\xi}) \cdot \partial_\alpha(\boldsymbol{n}_1 P) + \frac{B}{B+1} \nabla V(\boldsymbol{\xi}) \cdot \partial_\theta(\boldsymbol{n}_2 P)$$
$$- \frac{1}{2} A^2 \partial_\theta(\cot\theta P) + \frac{1}{2} \frac{A^2}{\sin^2\theta} \partial_{\alpha\alpha} P + \frac{1}{2} B A^2 \partial_{\theta\theta} P \ . \tag{5.1}$$

The stationary density is given by

$$P_{stat}(\boldsymbol{\xi}, \theta) = C \exp\big(-V(\boldsymbol{\xi})\big)\big(\sin\theta\big)^{\frac{1}{B}} \ . \tag{5.2}$$

We note that in the case $B = 1$ this is the Fokker-Planck equation and the stationary solution corresponding to the isotropic model (3.6). Next, we turn to the case B tending to 0. For $B = 0$ the system of stochastic differential equations (4.3) decouples into a closed system of ordinary differential equations in $(\boldsymbol{\xi}_3, \theta)$

$$\begin{aligned} d\boldsymbol{\xi}_{3t} &= \cos\theta_t\, dt \\ d\theta_t &= \frac{1}{2}A^2 \cot\theta_t\, dt \end{aligned} \tag{5.3}$$

and a remaining system similar to the 2D model (2.1),

$$\begin{aligned} d\boldsymbol{\xi}_{1t} &= \cos\alpha_t \sin\theta_t\, dt \\ d\boldsymbol{\xi}_{2t} &= \sin\alpha_t \sin\theta_t\, dt \\ \sin\theta_t d\alpha_t &= -\nabla V(\boldsymbol{\xi}_t)\cdot \boldsymbol{n}_1(\alpha_t)\, dt + A\, dW_t^{(1)} \ . \end{aligned} \tag{5.4}$$

The solution of (5.3) with initial values $\boldsymbol{\xi}_3(0) = \boldsymbol{\xi}_{3_0}$ and $\theta(0) = \theta_0$ is

$$\begin{aligned} \theta(t) &= \arccos\left(\exp\Big(-\frac{1}{2}A^2 t\Big)\cos\theta_0\right) \\ \boldsymbol{\xi}_3(t) &= \boldsymbol{\xi}_{3_0} + \frac{2}{A^2}\cos\theta_0 - \frac{2}{A^2}\exp\Big(-\frac{1}{2}A^2 t\Big)\cos\theta_0. \end{aligned}$$

In the large time limit $t \to \infty$ one obtains $\big(\boldsymbol{\xi}_3, \theta\big) = \big(\boldsymbol{\xi}_{3_0} + \frac{2}{A^2}\cos\theta_0, \frac{\pi}{2}\big)$. Plugging this into the remaining system (5.4) we recover the 2D model (2.1). This means that after a transition time or if the initial values are suitably chosen, the 2-D model is recovered. Moreover, one directly observes that the stationary solution of the modified model (5.2) tends towards the stationary solution of the 2D model (2.6) if B tends to zero:

$$C(\sin\theta)^{\frac{1}{B}} \stackrel{B\to 0}{\longrightarrow} \delta_{\pi/2} \ .$$

5.2. Large Diffusion Limit and Reduced Model. In this section we investigate the large turbulence case with the limit $A \to \infty$. We start from the Fokker-Planck equation (5.1) associated to the modified model and scale the equation using $t' = \varepsilon t$ and $A' = \sqrt{\varepsilon}A$. This yields

$$\begin{aligned} \varepsilon\partial_t P^\varepsilon = &-\boldsymbol{\tau}\cdot\nabla_\xi P^\varepsilon + \frac{1}{\sin\theta}\frac{1}{B+1}\nabla V(\boldsymbol{\xi})\cdot\partial_\alpha(\boldsymbol{n}_1 P^\varepsilon) + \frac{B}{B+1}\nabla V(\boldsymbol{\xi})\cdot\partial_\theta(\boldsymbol{n}_2 P^\varepsilon) \\ &-\frac{1}{2}\frac{A^2}{\varepsilon}\partial_\theta(\cot\theta P^\varepsilon) + \frac{1}{2}\frac{A^2}{\varepsilon\sin^2\theta}\partial_{\alpha\alpha}P^\varepsilon + \frac{1}{2}B\frac{A^2}{\varepsilon}\partial_{\theta\theta}P^\varepsilon. \end{aligned}$$

Plugging in the ansatz $P^\varepsilon = P^0 + \varepsilon P^1 + \dots$ the leading order problem is

$$\frac{1}{2}A^2\Big(-\partial_\theta(\cot\theta P^0) + \frac{1}{\sin^2\theta}\partial_{\alpha\alpha}P^0 + B\partial_{\theta\theta}P^0\Big) = 0$$

with solution

$$P^0(\boldsymbol{\xi},\theta,t) = C\,(\sin\theta)^{\frac{1}{B}} m^0(\boldsymbol{\xi},t) \ ,$$

where C is a normalization constant depending on the parameter B. To next order we have

$$\begin{aligned} 0 = &-\boldsymbol{\tau}\cdot\nabla_\xi P^0 + \frac{1}{\sin\theta}\frac{1}{B+1}\nabla V(\boldsymbol{\xi})\cdot\partial_\alpha(\boldsymbol{n}_1 P^0) + \frac{B}{B+1}\nabla V(\boldsymbol{\xi})\cdot\partial_\theta(\boldsymbol{n}_2 P^0) \\ &+\frac{1}{2}A^2\Big(-\partial_\theta(\cot\theta P^1) + \frac{1}{\sin^2\theta}\partial_{\alpha\alpha}P^1 + B\partial_{\theta\theta}P^1\Big) \ . \end{aligned}$$

Inserting P^0 yields

$$-\partial_\theta(\cot\theta P^1) + \frac{1}{\sin^2\theta}\partial_{\alpha\alpha}P^1 + B\partial_{\theta\theta}P^1 = C\frac{2}{A^2}\big(\nabla_\xi m^0 + \nabla V(\boldsymbol{\xi})m^0\big)\cdot\boldsymbol{\tau}(\sin\theta)^{\frac{1}{B}} \ .$$

The solution of this equation is given by

$$P^1(\boldsymbol{\xi},\theta,\alpha,t) = -\frac{1}{B+1}\frac{2}{A^2}C(\sin\theta)^{\frac{1}{B}}\boldsymbol{\tau}\cdot\big(\nabla_\xi m^0 + \nabla V(\boldsymbol{\xi})m^0\big) \ .$$

In a next step we integrate the scaled Fokker-Planck equation over the angles α and θ. Defining $m^\varepsilon := \int_0^{2\pi}\int_0^\pi P^\varepsilon d\theta d\alpha$ we obtain

$$\varepsilon\partial_t m^\varepsilon + \int_0^{2\pi}\int_0^\pi \boldsymbol{\tau}\cdot\nabla_\xi P^\varepsilon d\theta d\alpha = 0 \ .$$

To first order this is

$$\partial_t m^0 + \int_0^{2\pi}\int_0^\pi \boldsymbol{\tau}\cdot\nabla_\xi P^1 d\theta d\alpha = \mathcal{O}(\varepsilon) \ .$$

Applying the divergence relation $\nabla_\xi\cdot(\boldsymbol{\tau}P^1) = \boldsymbol{\tau}\cdot\nabla_\xi P^1 + P^1\nabla_\xi\cdot\boldsymbol{\tau} = \boldsymbol{\tau}\cdot\nabla_\xi P^1$ we have

$$\partial_t m^0 + \nabla_\xi\cdot\int_0^{2\pi}\int_0^\pi \boldsymbol{\tau}P^1 d\theta d\alpha = \mathcal{O}(\varepsilon)$$

and after replacing P^1 we get

$$\partial_t m^0 - \nabla_\xi\cdot\int_0^{2\pi}\int_0^\pi \boldsymbol{\tau}\frac{1}{B+1}\frac{2}{A^2}C(\sin\theta)^{\frac{1}{B}}\boldsymbol{\tau}\cdot\big(\nabla_\xi m^0 + \nabla V(\boldsymbol{\xi})m^0\big)d\theta d\alpha = \mathcal{O}(\varepsilon) \ .$$

After evaluating the integral and taking the limit $\varepsilon\to 0$ we obtain the reduced model

$$\partial_t m^0 - \frac{1}{A^2(1+2B)}\nabla_\xi\cdot\ D\big(\nabla_\xi m^0 + \nabla V(\boldsymbol{\xi})m^0\big) = 0$$

with

$$D = \operatorname{diag}\left\{1, 1, \tfrac{2B}{(1+B)}\right\}$$

or the system of stochastic differential equations

$$d\boldsymbol{\xi}_t = -\frac{1}{1+2B}\frac{1}{A^2}D\nabla V(\boldsymbol{\xi}_t)dt + \sqrt{\frac{2}{1+2B}}\frac{1}{A}\sqrt{D}d\boldsymbol{W}_t \tag{5.5}$$

We note, that for $B = 0$ we recover the reduced 2D model (2.7).

Remark 6. *The limiting process for $A\to\infty$ in the case of a moving conveyor belt is given by*

$$d\boldsymbol{\xi}_t = -\left(\frac{1}{1+2B}\frac{1}{A^2}D\nabla V(\boldsymbol{\xi}_t) - \kappa\boldsymbol{e}_1\right)dt + \sqrt{\frac{2}{1+2B}}\frac{1}{A}\sqrt{D}d\boldsymbol{W}_t \ , \tag{5.6}$$

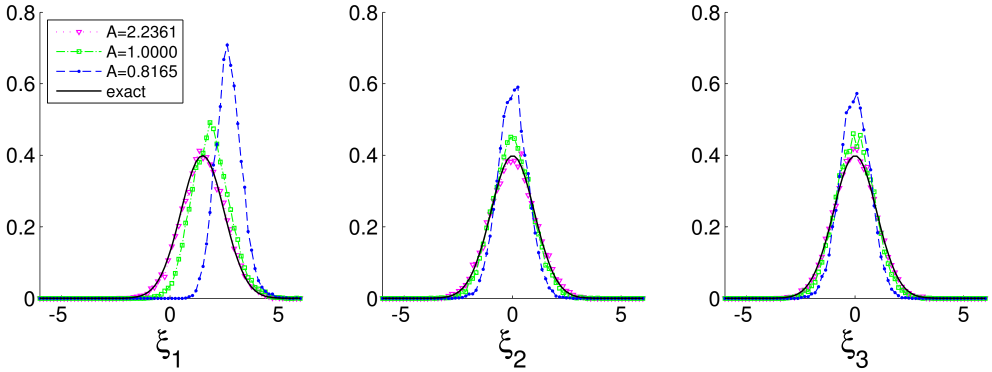

Fig. 5.1: *Stationary marginal densities of $\boldsymbol{\xi}$-components for different values of A and fixed $q = 0.5$*

compare [3] for the two-dimensional case.

To investigate the practical relevance of the reduced model numerically we compare the isotropic 3D model process with moving belt (3.5) with the reduced model (5.6) with $B = 1$. The potential is chosen as $V(\boldsymbol{\xi}) = |\boldsymbol{\xi}|^2/2$. The stationary density of (5.6) reads

$$P_{stat}(\boldsymbol{\xi}) = C \exp\left(-\frac{\left(\xi_1 - (2B+1)\kappa A^2\right)^2}{2} - \frac{\xi_2^2}{2} - \frac{\xi_3^2}{2} \right) ,$$

which is independent of the scaling for $\kappa A^2 = q$, $q \in \mathbb{R}$. Figure 5.1 shows the stationary marginal densities for the components ξ_1, ξ_2 and ξ_3 for (3.5) with different values of A and fixed $q = 0.5$ and the above stationary density of (5.6) for $B = 1$. Whereas the marginal densities differ for $A < 1$, the approximation is qualitatively better for increasing A. Good agreement can be observed for $A > 2$. Similar results can be shown for the modified 3D model ($B < 1$). Thus the reduced models might be seen as alternatives to the original models even for moderate values of A. However, we note that in the limit we loose regularity of the fiber path. Moreover, the inextensibility of the fiber is not anymore preserved.

Remark 7. *In [6] also the small diffusion limit $A \to 0$ has been considered for the 2D case using a representation of the equations as a stochastic Hamiltonian system and the method of stochastic averaging, see also [1, 2]. Similarly, the 3D system can be rewritten in Hamiltonian form. However, in contrast to the 2D case where the reduced Hamiltonian system has been a 2-dimensional system, it is in the present case a 4-dimensional equation allowing for 3 invariants, which are not as straightforwardly determined.*

5.3. The Large Coiling Force Limit. In this section we investigate a hyperbolic scaling, the large coiling force and large diffusion limit with $A' = A/\sqrt{\epsilon}$ and

$V' = V/\epsilon$. We start from the scaled Fokker-Planck equation

$$\partial_t P^\varepsilon = -\boldsymbol{\tau} \cdot \nabla_\xi P^\varepsilon + \frac{1}{\varepsilon}\frac{1}{\sin\theta}\frac{1}{B+1}\nabla V(\boldsymbol{\xi}) \cdot \partial_\alpha(\boldsymbol{n}_1 P^\varepsilon) + \frac{1}{\varepsilon}\frac{B}{B+1}\nabla V(\boldsymbol{\xi}) \cdot \partial_\theta(\boldsymbol{n}_2 P^\varepsilon)$$
$$-\frac{1}{2}\frac{A^2}{\varepsilon}\partial_\theta(\cot\theta P^\varepsilon) + \frac{1}{2}\frac{A^2}{\varepsilon\sin^2\theta}\partial_{\alpha\alpha}P^\varepsilon + \frac{1}{2}B\frac{A^2}{\varepsilon}\partial_{\theta\theta}P^\varepsilon.$$

To zeroth order this is

$$\frac{1}{\sin\theta}\frac{1}{B+1}\nabla V(\boldsymbol{\xi}) \cdot \partial_\alpha(\boldsymbol{n}_1 P^0) + \frac{B}{B+1}\nabla V(\boldsymbol{\xi}) \cdot \partial_\theta(\boldsymbol{n}_2 P^0)$$
$$-\frac{1}{2}A^2\partial_\theta(\cot\theta P^0) + \frac{1}{2}\frac{A^2}{\sin^2\theta}\partial_{\alpha\alpha}P^0 + \frac{1}{2}BA^2\partial_{\theta\theta}P^0 = 0$$

with the solution

$$P^0(\boldsymbol{\xi}, \alpha, \theta, t) = \frac{\rho(\boldsymbol{\xi}, t)}{N(\boldsymbol{\xi})}(\sin\theta)^{\frac{1}{B}} \exp\left(-\frac{1}{A^2}\frac{2}{B+1}\boldsymbol{\tau} \cdot \nabla V\right)$$

with

$$N(\boldsymbol{\xi}) = \int (\sin\theta)^{\frac{1}{B}} \exp\left(-\frac{1}{A^2}\frac{2}{B+1}\boldsymbol{\tau} \cdot \nabla V\right) d\alpha d\theta.$$

Integrating the scaled Fokker-Planck equation over α and θ yields up to order ϵ

$$\partial_t \rho + \nabla_\xi \cdot \int \boldsymbol{\tau} P^0 d\alpha d\theta = 0\ .$$

This can be rewritten as

$$\partial_t \rho + \nabla_\xi \cdot (\rho\, \boldsymbol{U}) = 0$$

with

$$\boldsymbol{U} = \boldsymbol{U}(\boldsymbol{\xi}) = \frac{1}{N(\boldsymbol{\xi})}\int \boldsymbol{\tau}(\sin\theta)^{\frac{1}{B}} \exp\left(-\frac{1}{A^2}\frac{2}{B+1}\boldsymbol{\tau} \cdot \nabla V\right) d\theta d\alpha.$$

Under suitable assumptions concerning the symmetry of the process, for example, in the isotropic case $B = 1$ and assuming that $V(\boldsymbol{\xi}) = V(|\boldsymbol{\xi}|)$ we have $N(\boldsymbol{\xi}) = N(|\boldsymbol{\xi}|)$ and we can rewrite $\boldsymbol{U}$ as

$$\boldsymbol{U}(\boldsymbol{\xi}) = \lambda(|\boldsymbol{\xi}|)\boldsymbol{\xi}$$

with

$$\lambda(|\boldsymbol{\xi}|) = \frac{1}{V'(|\boldsymbol{\xi}|)|\boldsymbol{\xi}|N(|\boldsymbol{\xi}|)}\int \nabla V \cdot \boldsymbol{\tau}\sin\theta\, \exp\left(-\frac{1}{A^2}\boldsymbol{\tau} \cdot \nabla V\right) d\theta d\alpha.$$

Thus, the limit equation is in such a case given by

$$\partial_t \rho + \nabla_\xi \cdot \big(\rho\, \lambda(|\boldsymbol{\xi}|)\boldsymbol{\xi}\big) = 0. \tag{5.7}$$

In this case one shows that λ is negative, i.e. the vector field $\boldsymbol{U}$ points towards the origin. For $B = 1$ and the potential $V(\boldsymbol{\xi}) = |\boldsymbol{\xi}|^2/2$ we plot $|\boldsymbol{\xi}|\lambda(|\boldsymbol{\xi}|)$ in Figure 5.2. For general $B < 1$, one can show that the vector field $\boldsymbol{U}$ is symmetric with respect to the $\boldsymbol{e}_3$-axis, compare Figure 5.2.

Remark 8. *An equivalent result can be proven with the same method in the 2D case.*

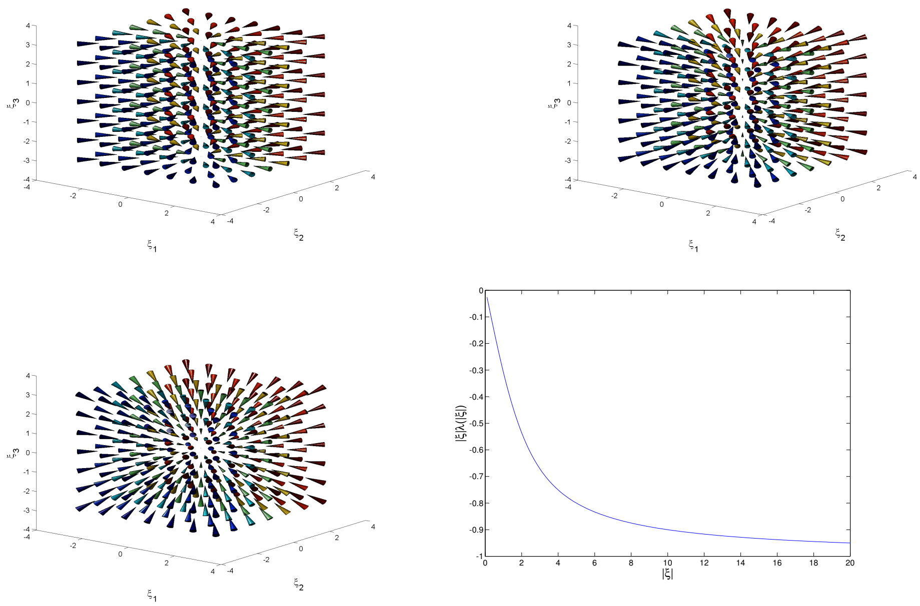

Fig. 5.2: *Plots of the vector field* $\boldsymbol{U}$ *for different parameter* $B = 0$; 0.1; 1 *and plot of* $|\boldsymbol{\xi}|\lambda(|\boldsymbol{\xi}|)$ *on the bottom right for the isotropic case* ($B = 1$) *and fixed* A

5.4. Relations between the Models. Figure 5.3 shows the scaling limits of the modified 3D model (4.3).

6. Numerical Simulations and Identification of the Parameters. In the 2D case the parameter A and the shape of the potential V have been estimated in [10] for different production processes. There, full simulations of a single representative fiber have been performed with the software tool FIDYST[1], see [12, 8] for a description of the algorithms. The noise amplitude A and the potential V in the 2D model (2.4) have been identified on the basis of the full simulation. Figure 6.1 shows as an example the fiber trajectories computed by the calibrated 2D model and, in comparison, an underlying full FIDYST simulation. The fiber mass distribution is captured qualitatively well in the surrogate model. The potential in ξ_3 might be assumed as confining potential which models the impenetrable conveyor belt.

It remains to give a method to determine the distribution of the θ-angle in a real material and translate this into the corresponding parameter B. Therefore we assume that the measurement of the θ-angle in a real nonwoven leads to an axisymmetric distribution in θ with mean $m_\theta = \pi/2$ and variance $var_\theta = \sigma_\theta^2$. Then the parameter B in the stationary θ-distribution $P_B(\theta) = C \sin\theta^{\frac{1}{B}}$ is chosen such that the variance of this distribution coincides with var_θ.

In Figure 6.2 an example of a virtual fleece generated by the modified 3D model is shown, where we simulate 10 fibers on a moving conveyor belt with assumed speed ratio $\kappa = 0.0238$. The distance between two spinning nozzles is chosen as $d = 2.5 \cdot$

[1]FIDYST:Fiber Dynamics Simulation Tool developed at Fraunhofer ITWM, Kaiserslautern

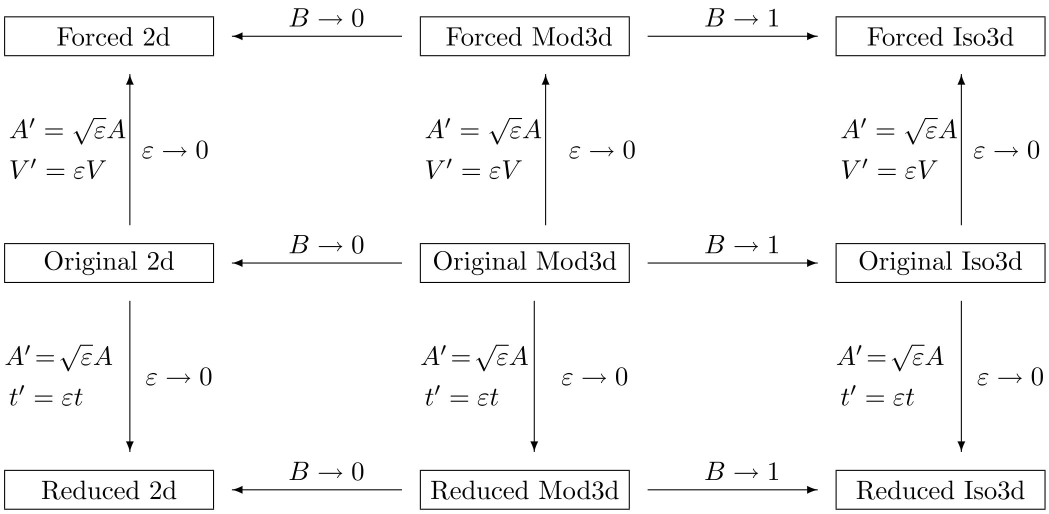

Fig. 5.3: *Asymptotic limits of the 3D fiber model for different scalings.*

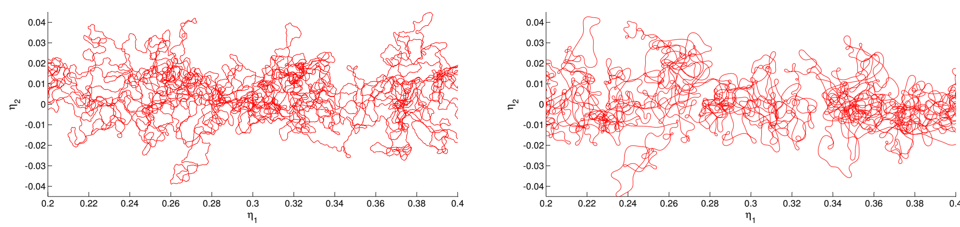

Fig. 6.1: *Comparison of fiber path associated to the adapted 2D surrogate model (left) and the FIDYST simulation (right)*

10^{-3} and the variance of the θ-distribution as $\sigma_\theta^2 = 0.0169$ which corresponds to a parameter $B = 0.0171$. The throwing ranges σ_1, σ_2 in the standard buckling potential $V(\boldsymbol{\xi}) = (\xi_1^2/\sigma_1^2 + \xi_2^2/\sigma_2^2)/2$ and the noise amplitude A are determined by the parameter identification from FIDYST data. The throwing range in z-direction or the fleece thickness is supposed to be $d_{fleece} = 0.01$.

7. Conclusion and Outlook . In this paper we derived a new 3D model for the fiber lay down process in technical textile production taking into account the anisotropic orientation of the fibers in the resulting fleece. In future work we plan to apply the model to real fiber process problems, where the distribution of the angle θ can be obtained by a computer tomography of the non-woven and associated image analysis. Moreover, from the theoretical point of view the convergence to equilibrium of the 3D models will be discussed with methods developed in [4]. See [5] for the 2-D

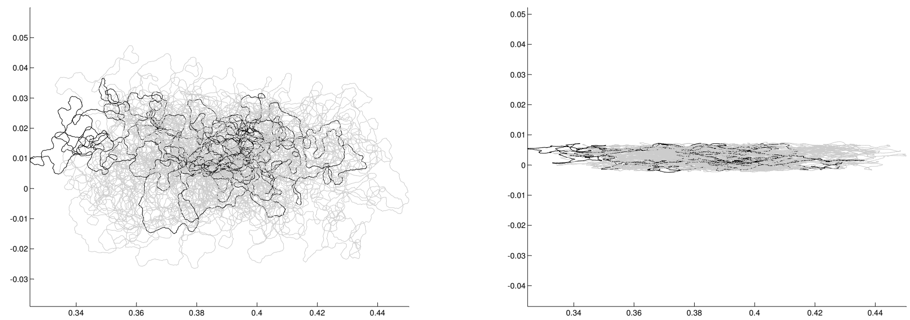

Fig. 6.2: *Example of a virtual fleece (10 fibers) with top view (left) and side view (right).* A representative single fiber is emphasized as darker curve.

case. The drawback of non-differentiable fiber path can be overcome by replacing the Wiener Process by an Ornstein-Uhlenback process leading to a more realistic smooth model [11] analogous to the 2-D case, see [8].

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