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Vorwort

Das Tätigkeitsfeld des Fraunhofer-Instituts für Techno- und Wirtschaftsmathematik ITWM umfasst anwendungsnahe Grundlagenforschung, angewandte Forschung sowie Beratung und kundenspezifische Lösungen auf allen Gebieten, die für Techno- und Wirtschaftsmathematik bedeutsam sind.

In der Reihe »Berichte des Fraunhofer ITWM« soll die Arbeit des Instituts kontinuierlich einer interessierten Öffentlichkeit in Industrie, Wirtschaft und Wissenschaft vorgestellt werden. Durch die enge Verzahnung mit dem Fachbereich Mathematik der Universität Kaiserslautern sowie durch zahlreiche Kooperationen mit internationalen Institutionen und Hochschulen in den Bereichen Ausbildung und Forschung ist ein großes Potenzial für Forschungsberichte vorhanden. In die Berichtreihe sollen sowohl hervorragende Diplom- und Projektarbeiten und Dissertationen als auch Forschungsberichte der Institutsmitarbeiter und Institutsgäste zu aktuellen Fragen der Techno- und Wirtschaftsmathematik aufgenommen werden.

Darüber hinaus bietet die Reihe ein Forum für die Berichterstattung über die zahlreichen Kooperationsprojekte des Instituts mit Partnern aus Industrie und Wirtschaft.

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 Stochastic Model for the Fiber Lay-down Process in the Nonwoven Production

T. Götz* A. Klar*† N. Marheineke* R. Wegener†

October 23, 2006

Abstract

In this paper we present and investigate a stochastic model for the lay-down of fibers on a conveyor belt in the production process of nonwovens. The model is based on a stochastic differential equation taking into account the motion of the fiber under the influence of turbulence. A reformulation as a stochastic Hamiltonian system and an application of the stochastic averaging theorem lead to further simplifications of the model. Finally, the model is used to compute the distribution of functionals of the process that might be helpful for the quality assessment of industrial fabrics.

Keywords. fiber dynamics, stochastic Hamiltonian system, stochastic averaging.

AMS Classification. 37H10, 60H30, 70H05

1 Introduction

The understanding of the forms generated by the lay-down of flexible fibers onto a moving conveyor belt is of great interest in the production process of nonwovens that find their applications e.g. in composite materials (filters), textile and hygiene industry [3]. In the melt-spinning process of nonwoven materials, hundreds of individual endless fibers being obtained by the continuous extrusion of a melted polymer are stretched and entangled by highly

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turbulent air flows to finally form a web on the conveyor belt. The quality of this web and the resulting nonwoven material – in terms of homogeneity and load capacity – depends essentially on the dynamics and the deposition of the fibers.

A mathematical model and numerical simulations for the nonwoven production process are presented in [9]. The paper focuses on the fiber spinning and lay-down, where the fiber dynamics in the deposition region close to the conveyor belt is dominated by the turbulent air flow. For the description of the interaction between fibers and turbulent flow a stochastic force model is derived and analyzed in [13] as well as experimentally validated in [14]. Applying this concept, the fiber fabric can be in principle numerically generated and its quality investigated in the spirit of the multi-scale image analysis of [16]. However, these simulations lead usually to excessively large computation times, when all physical details of the production process are considered. Thus, simplified models for the lay-down process are needed. In particular, this is true for optimization and control procedures where many different simulations are needed. Experimental studies on the forms of threads laid on a moving belt as well as a simplified general theory for the buckling of the fibers can be found in [8]. The coiling behavior of flexible rods is investigated in [12].

Motivated by the research work done in the field of woven textile composites [6], e.g. modeling [11], numerical and asymptotical stress analysis [17], stiffness / load capacity investigations [5], we focus in this paper on the modeling of nonwoven textiles and the determination of textile properties, e.g. weight distribution, that are important for the quality assessment of industrial nonwoven fabrics. In particular, we present a new simplified stochastic model for the fiber lay-down process, i.e. for the generation of the fiber web on the conveyor belt that is assumed to be non-moving for simplicity. Taking into account the fiber motion under the influence of turbulence, the process is described by a stochastic differential system in Section 2. Its associated Kolmogoroff equation and stationary solution are investigated in Section 3. Moreover, we include remarks on the identification of the process parameters. Section 4 contains an investigation of the scaled stochastic Hamiltonian system using stochastic averaging. In Section 5 we conclude with the computation of the probability distribution of process functionals.

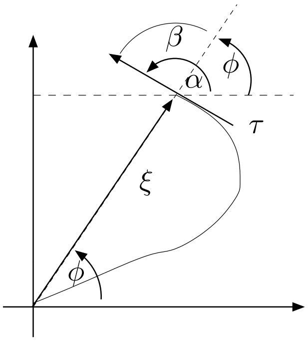


Figure 1: Fiber scenario on the conveyor belt.

2 Stochastic Model for Fiber Lay-down

Focusing on a single slender elastic inextensible fiber in an isotropic lay-down process, the fiber on the non-moving conveyor belt can be described by an arc-length parameterized curve $\xi : \mathbb{R}_0^+ \to \mathbb{R}^2$ as visualized in Figure 1. Due to its inextensibility, $\|\partial_t \xi\| = 1$ holds. The web-forming is modeled as

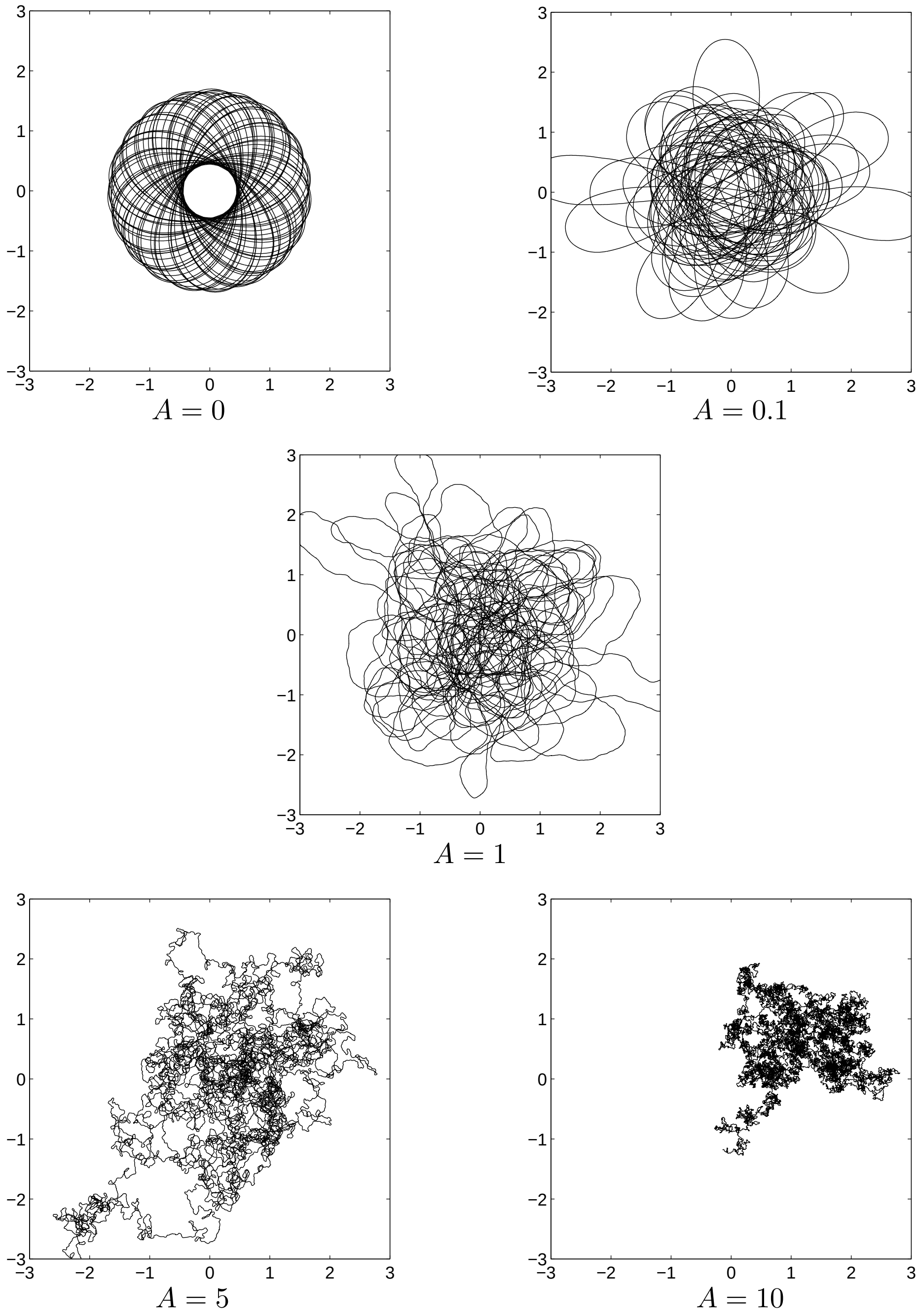
$$\begin{aligned}\partial_t \xi &= \tau(\alpha)\\ \partial_t \alpha &= -b(\|\xi\|)\frac{\xi}{\|\xi\|} \cdot \tau^{\perp}(\alpha),\end{aligned}$$

where $\tau(\alpha) = (\cos\alpha, \sin\alpha)^T$ denotes the normalized tangent on the fiber. Since a curved fiber tends back to its starting point, the change of the angle α is assumed to be proportional to $\xi \cdot \tau^{\perp}(\alpha)$ with $\tau^{\perp}(\alpha) = (-\sin\alpha, \cos\alpha)^T$. The amplitude of this drive is prescribed by a continuously differentiable function $b : \mathbb{R}_0^+ \to \mathbb{R}$ with $b(r) > 0$ for $r > 0$ and $b'(r) \geq 0$ for $r \geq 0$. Let r_0 be the argument that satisfies $b(r_0) = 1/r_0$. The amplitude depends on the process and needs to be adapted to the experimental parameters. In case of an anisotropic lay-down process the scalar-valued function b has to be replaced by an appropriate matrix-valued one, i.e.

$$\partial_t \alpha = -\frac{\xi}{\|\xi\|} M(\|\xi\|)\tau^{\perp}(\alpha),$$

where $M(r) \in \mathbb{R}^{2\times 2}$ denotes a positive definite matrix.

Considering a turbulent flow in the deposition region of the fiber close to the conveyor belt, the fiber lay-down is additionally affected by a stochastic force that can be modeled by a Wiener process W_t in $\mathbb{R}$ with amplitude A.



$A = 0$ $A = 0.1$

$A = 1$

$A = 5$ $A = 10$

Figure 2: Representative path behavior for balanced ($A = 1$) as well as deterministic ($A < 1$) and stochastic ($A > 1$) dominated (ξ, α)-systems.

The resulting stochastic differential system reads

$$\begin{aligned}
\mathrm{d}\xi_t &= \tau(\alpha_t)\,\mathrm{d}t \\
\mathrm{d}\alpha_t &= -b(\|\xi_t\|)\frac{\xi_t}{\|\xi_t\|}\cdot\tau^{\perp}(\alpha_t)\,\mathrm{d}t + A\,\mathrm{d}W_t
\end{aligned}$$

where the conservation of length $\|\partial_t\xi\| = 1$ is still valid. Since length, i.e. fiber (arc-)length t and position ξ, is the only dimension in the lay-down process, the system can be non-dimensionalized by scaling it with the typical deposition radius r_0. Then, we have $b^\star(r^\star) = r_0\,b(r_0 r^\star)$ and $A^\star = \sqrt{r_0}A$. Consequently, $b^\star(1) = 1$ holds, and the dimensionless noise amplitude $A^\star$ characterizes the relation between stochastic and deterministic rates in the behavior of the system. Figure 2 shows examples for the pathwise behavior of the solution for varying noise A with constant drive $b(r) = 1$ and fixed fiber length. Physically relevant scenarios include typically parameters ranging from $A = 0.1$ to $A = 5$ depending on the size of the turbulent force exerted on the fiber. Note that for convenience we have skipped the superscript star * denoting the dimensionless quantities. Moreover, we embed our model in the context of dynamical systems and stochastic processes and use in the following the notation and interpretation of time for the arc-length parameter.

Introducing polar coordinates $\xi = (r\cos\phi, r\sin\phi)^T$, $r = \|\xi\|$ and the angle $\beta = \alpha - \phi$ with ϕ in ξ-space (Figure 1), the given stochastic differential system can be rewritten in terms of $(r,\beta) \in [0,\infty)\times[0,2\pi]$

$$\mathrm{d}r_t = \cos\beta_t\,\mathrm{d}t \tag{1a}$$

$$\mathrm{d}\beta_t = \left(b(r_t) - \frac{1}{r_t}\right)\sin\beta_t\,\mathrm{d}t + A\,\mathrm{d}W_t \tag{1b}$$

$$\mathrm{d}\phi_t = \frac{\sin\beta_t}{r_t}\,\mathrm{d}t. \tag{1c}$$

Due to symmetry, we can restrict ourselves to $\beta \in [0,\pi]$. Since the equation for ϕ_t is decoupled from the remaining (r_t,β_t)-process, this transformation leads to a dimension reduction of the problem. The deterministic (r,β)-system with $A = 0$ moves on closed orbits in the (r,β)-plane, as illustrated in Figure 3. Its fixpoint is $(r,\beta) = (1,\pi/2)$. The periodic orbits are given by the level sets, "energy", $H(r,\beta) = h \in [0,\infty)$ of the Hamiltonian

$$H(r,\beta) = B(r) - \ln r - \ln\sin\beta$$

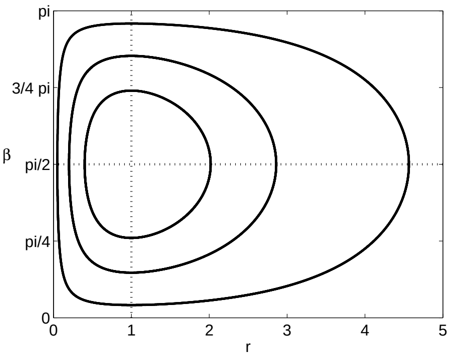


Figure 3: Orbits of the deterministic (r, β)-system for different values of h.

where $B(r) = \int_1^r b(r')\,\mathrm{d}r'$. For fixed energy h, the radius r takes values in $[r_{\min}(h),\ r_{\max}(h)]$ with $0 < r_{\min}(h) < 1 < r_{\max}(h)$.

We can rewrite (1) in Hamiltonian coordinates $(r, z) \in [0, \infty) \times (-\infty, \infty)$ with $z = \ln\tan(\beta/2)$, i.e. $\beta = 2\arctan(e^z)$, $z' = 1/\sin\beta$, $\beta' = \sin\beta$. Using Ito's formula gives then

$$\mathrm{d}r_t = \cos\beta(z_t)\,\mathrm{d}t \tag{2a}$$

$$\mathrm{d}z_t = \left(b(r_t) - \frac{1}{r_t}\right)\mathrm{d}t - \frac{A^2\cos\beta(z_t)}{2\sin^2\beta(z_t)}\,\mathrm{d}t + \frac{A}{\sin\beta(z_t)}\,\mathrm{d}W_t \tag{2b}$$

and consequently with $H(r, z) = B(r) - \ln(r) - \ln\sin(2\arctan(e^z))$

$$\begin{aligned}\mathrm{d}r_t &= -\partial_z H(r_t, z_t)\,\mathrm{d}t\\ \mathrm{d}z_t &= \partial_r H(r_t, z_t)\,\mathrm{d}t - \frac{A^2\cos\beta(z_t)}{2\sin^2\beta(z_t)}\,\mathrm{d}t + \frac{A}{\sin\beta(z_t)}\,\mathrm{d}W_t.\end{aligned}$$

Remark 1 *Linearizing the system in* (2) *around the fixpoint* $(r, z) = (1, 0)$ *we obtain a Hamiltonian system with the Hamiltonian function*

$$H_{lin}(r, z) = \frac{1}{2}\left(b'(1) + 1\right)(r-1)^2 + \frac{1}{2}z^2.$$

being a harmonic oscillator. Its period of motion [4] is $T_{lin} = 2\pi/\sqrt{b'(1)+1}$.

In general, as in the nonlinear case considered above, the period of motion T_H *is not constant but depends on the energy* h. *An integral representation for* T_H *stated in* (5) *can be derived analytically, see below and [4] for further investigations. For small* h, *the nonlinear period of motion tends obviously to the linearized one.*

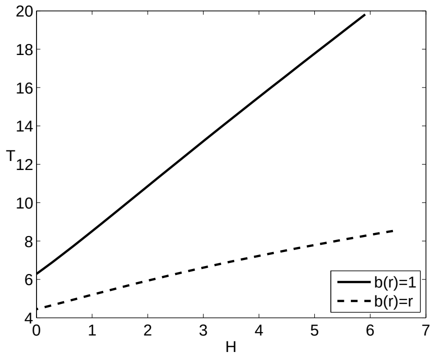


Figure 4: Period of motion $T_H(h)$ for $b(r) = 1$ (–) and $b(r) = r$ (- -).

Example 1 *Considering the linearization, the period of motion is* $T_{lin} = 2\pi$ *for* $b(r) = 1$ *and* $T_{lin} = 2\pi/\sqrt{2}$ *for* $b(r) = r$*. For the corresponding nonlinear cases, numerical evaluations of* T_H *are presented in Figure 4.*

3 Kolmogoroff Equation and Stationary Solution

We start the investigation of the fiber lay-down model by considering the associated Fokker-Planck equation and determining its stationary distribution as $t \to \infty$.

The forward or Fokker-Planck equation for the density $p_1 : (t, r, \beta) \mapsto p_1(t, r, \beta)$ of system (1) is given by

$$\partial_t p_1 + \cos\beta\, \partial_r p_1 + \left(b(r) - \frac{1}{r}\right) \partial_\beta (\sin\beta\, p_1) = \frac{A^2}{2} \partial_{\beta\beta} p_1,$$

where $p_1(t = 0, r, \beta)$ is prescribed. Its stationary solution reads

$$p_{S_1}(r, \beta) = Cre^{-B(r)} \tag{3}$$

with the normalization constant C. In the Hamiltonian coordinates $(r,\ z = \ln\tan(\beta/2))$ of system (2) we have

$$p_{S_2}(r, z) = p_{S_1}(r, \beta(z))\, \beta'(z) = Cre^{-B(r)} \sin\beta(z) = Ce^{-H(r,z)}$$

due to the transformation of measures. Note that the subscript of the stationary solution indicates the corresponding system.

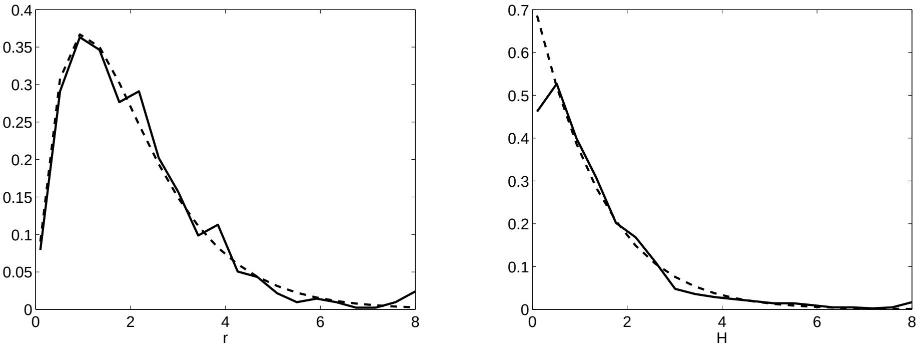


Figure 5: Stationary distributions, analytical (- -) vs numerical (–). Left: p_{S_1}. Right: p_{S_H} for $b(r) = 1$.

Concerning the energy-related stationary distribution we have

$$\begin{aligned} p_{S_H}(h) &= \frac{\mathrm{d}}{\mathrm{d}h} \int_{H(r,z)<h} p_{S_2}(r,z)\, \mathrm{d}r\, \mathrm{d}z = C\, e^{-h} \frac{\mathrm{d}}{\mathrm{d}h} \int_{H(r,z)<h} \mathrm{d}r\, \mathrm{d}z \\ &= C\, e^{-h}\, T_H(h) \end{aligned} \tag{4}$$

because the period of motion of the deterministic system is given by

$$T_H(h) = \frac{\mathrm{d}}{\mathrm{d}h} \int_{H(r,z)<h} \mathrm{d}r\, \mathrm{d}z. \tag{5}$$

see e.g. [4]. This follows from the coming consideration. Take the reduced one-parametric family of deterministic processes with initial condition $H(r(0), 0) = h$, then every point (r, z) in the phase-space can be prescribed by h and the first time t to reach this point. As a simply consequence of the conservation of energy and the canonical structure of the Hamiltonian system, the functional determinant of the corresponding transformation is one. Hence, $\int_{H(r,z)<h} \mathrm{d}r\, \mathrm{d}z = \int_0^h \int_0^{T_H(h')} \mathrm{d}t\, \mathrm{d}h'$ which yields (5).

A numerical simulation of the lay-down process (1) with $b(r) = 1$ enables the comparison of the analytical stationary distributions p_{S_1} with the stationary distribution of the r_t-process and, respectively, the comparison of p_{S_H} with the numerically computed stationary distribution of the energy process H_t, see Figure 5.

Remark 2 *The identification of the parameters, i.e. drive b and noise amplitude A, in the lay-down model is important for the realistic description* *of industrially relevant scenarios. Comparing the stationary distribution* p_{S_1} *with experimentally available data we can determine the function* B *and thus its derivative* b*. The noise amplitude* A *can be computed from*

$$(\mathrm{d}\alpha_t)^2 = A^2 \,\mathrm{d}t$$

or alternatively from

$$\lim_{h\to 0} \frac{\mathbb{E}\left[(\alpha_{t+h} - \alpha_t)^2\right]}{h} = A^2,$$

presupposing that the real process is prescribed by white noise. In a forthcoming publication we will identify both parameters from the simulation of the complete production process of nonwovens, according to [9, 13], for different industrially relevant cases.

4 Stochastic Averaging and Energy Equation

In the following we consider lay-down processes (1) with little noise $A = \sqrt{\epsilon}\tilde{A}$ on associated longer "time" scales $t = \tilde{t}/\epsilon$ with $0 < \epsilon \ll 1$, see Figure 2 for the pathwise behavior for different noise levels. In this case, a simplified approximation of the dynamics can be given by stochastic averaging. This leads to a reduced system as $\epsilon \to 0$, i.e. stochastic differential equations for the limit energy process for which we determine the drift and variance coefficients.

Dropping the tildes, the rescaled $(r_t^\epsilon, \beta_t^\epsilon)$-system reads

$$\begin{aligned}
\mathrm{d}r_t^\epsilon &= \frac{1}{\epsilon} \cos\beta_t^\epsilon \,\mathrm{d}t \\
\mathrm{d}\beta_t^\epsilon &= \frac{1}{\epsilon}\left(b(r_t^\epsilon) - \frac{1}{r_t^\epsilon}\right) \sin\beta_t^\epsilon \,\mathrm{d}t + A\,\mathrm{d}W_t.
\end{aligned}$$

Applying Ito's formula the resulting energy process $H_t^\epsilon = H(r_t^\epsilon, \beta_t^\epsilon)$ fulfills the equation

$$\begin{aligned}
\mathrm{d}H_t^\epsilon &= \partial_r H \,\mathrm{d}r_t^\epsilon + \partial_\beta H \,\mathrm{d}\beta_t^\epsilon + \frac{1}{2}\partial_{\beta\beta} H \,(\mathrm{d}\beta_t^\epsilon)^2 \\
&= \left(b(r_t^\epsilon) - \frac{1}{r_t^\epsilon}\right) \mathrm{d}r_t^\epsilon - \cot\beta_t^\epsilon \,\mathrm{d}\beta_t^\epsilon + \frac{1}{2\sin^2\beta_t^\epsilon}\,(\mathrm{d}\beta_t^\epsilon)^2 \\
&= \frac{A^2}{2\sin^2\beta_t^\epsilon}\,\mathrm{d}t - A\cot\beta_t^\epsilon \,\mathrm{d}W_t.
\end{aligned}$$

Using formally the stochastic averaging theorem, see e.g. [10] or [15] and [1, 2] for an application to stochastic Hamiltonian systems, the limit equation for H_t^ϵ as ϵ tends to 0 is given by

$$\mathrm{d}H_t^0 = a_H(H_t^0)\,\mathrm{d}t + \sigma_H(H_t^0)\,\mathrm{d}W_t$$

with drift and variance

$$a_H(h) = \frac{A^2}{2T_H(h)} \int_0^{T_H(h)} \frac{1}{\sin^2\beta(t)}\,\mathrm{d}t, \quad \sigma_H^2(h) = \frac{A^2}{T_H(h)} \int_0^{T_H(h)} \cot^2\beta(t)\,\mathrm{d}t \tag{6}$$

In these formulas β denotes the solution of the deterministic (r,β)-process for fixed energy h. The expressions for a_H and σ_H^2 can be formulated more explicitely as

$$a_H(h) = \frac{A^2}{2}\left(1 + \overline{T_H}(h)\right), \qquad \sigma_H^2(h) = A^2\,\overline{T_H}(h), \tag{7}$$

with $$\overline{T_H}(h) = \frac{e^{2h}}{T_H(h)} \int_0^h T_H(h')e^{-2h'}\,\mathrm{d}h'.$$

The derivation of (7) is based on two equations for the parameters. Firstly, due to their form in (6) we have

$$2a_H(h) - \sigma_H^2(h) = A^2. \tag{8}$$

The second equation we obtain from the stationary distribution. Consider the Fokker-Planck equation corresponding to H_t^0

$$\partial_t p_H + \partial_h\left(a_H(h)p_H\right) = \frac{1}{2}\partial_{hh}\left(\sigma_H^2(h)p_H\right),$$

the solution of the stationary equation $2a_H(h)\,p_{S_H} = \partial_h\left(\sigma_H^2(h)\,p_{S_H}\right)$ reads

$$p_{S_H}(h) = \tilde{C}\exp\left(-\int^h \frac{(\sigma_H^2)'(h') - 2a_H(h')}{\sigma_H^2(h')}\,dh'\right)$$

with the normalizing constant $\tilde{C}$. On the other hand the stationary solution for the $(r_t^\epsilon, \beta_t^\epsilon)$-process is independent of ϵ and according to (4)

$$p_{S_H}(h) = Ce^{-h}\,T_H(h)$$

holds for all ϵ and therefore also for the limit process. Hence, from the comparison of the different expressions for p_{S_H} we obtain

$$\frac{(\sigma_H^2)'(h) - 2a_H(h)}{\sigma_H^2(h)} = 1 - (\ln T_H(h))'. \tag{9}$$

Equations (8) and (9) yield a differential equation for the variance

$$(\sigma_H^2)'(h) = A^2 + 2\sigma_H^2(h) - (\ln T_H(h))'\,\sigma_H^2(h)$$

from which the explicit formulas in (7) can be concluded.

Summarizing, the energy equation for the limit process H_t^0 and its associated Fokker-Planck equation read

$$\begin{aligned} \mathrm{d}H_t^0 =& \frac{A^2}{2}(1 + \overline{T_H}(H_t^0))\,\mathrm{d}t + A\sqrt{\overline{T_H}(H_t^0)}\,\mathrm{d}W_t \\ \partial_t p_H +& \frac{A^2}{2}\partial_h\left((1 + \overline{T_H}(h))\,p_H\right) = \frac{A^2}{2}\partial_{hh}\left(\overline{T_H}(h)\,p_H\right). \end{aligned}$$

The introduction of an alternative energy process

$$G_t^\epsilon = e^{-H_t^\epsilon} = r_t^\epsilon\, e^{-B(r_t^\epsilon)}\,\sin\beta_t^\epsilon$$

is more suitable for the following numerical simulations since it is restricted on the interval $[0,1]$. Analogously to the previous averaging procedure or directly from H_t^ϵ by means of the Ito-calculus, i.e.

$$\mathrm{d}G_t^0 = -e^{-H_t^0}\mathrm{d}H_t^0 + \frac{1}{2}e^{-H_t^0}(\mathrm{d}H_t^0)^2,$$

we determine the limit process G_t^0 as

$$\mathrm{d}G_t^0 = a_G(G_t^0)\,\mathrm{d}t + \sigma_G(G_t^0)\,\mathrm{d}W_t$$

with drift and variance

$$a_G(g) = -\frac{A^2}{2}g, \qquad \sigma_G^2(g) = \frac{A^2 g^2}{T_G(g)}\int_0^{T_G(g)} \cot^2\beta(t)\,\mathrm{d}t \tag{10}$$

or, respectively,

$$\begin{aligned} \sigma_G^2(g) &= A^2\overline{T_G}(g), \\ \overline{T_G}(g) &= \frac{1}{T_G(g)}\int_g^1 T_G(g')\,g'\,\mathrm{d}g' \end{aligned} \tag{11}$$

in accordance to (8) and (9) for H_t^0. The period of motion T_G is defined by the associated transformation $T_G(g) = T_H(-\ln g)$. The stationary solution of the associated Fokker-Plank equation

$$\partial_t p_G - \frac{A^2}{2}\,\partial_g(g p_G) = \frac{A^2}{2}\,\partial_{gg}(\overline{T_G}(g)p_G)$$

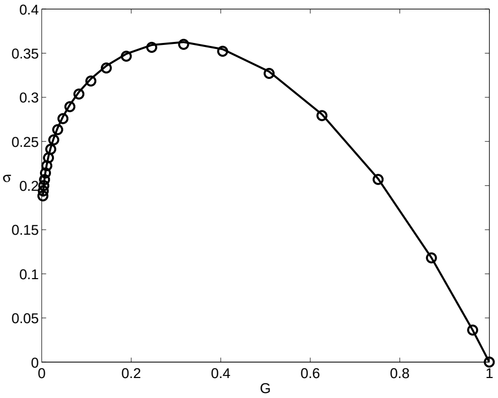


Figure 6: σ_G for $A = 1$, computed via (11) (–), via (10) (o).

reads, as expected,

$$p_{S_G}(g) = C\, T_G(g), \quad g \in [0, 1].$$

A more detailed investigation of the above Fokker-Planck equation with suitable boundary condition will be considered in a forthcoming publication.

Remark 3 *For $T_H(h)$ tending to infinity as $h \to \infty$ – as motivated by Figure 4 – and $T_G(g)\, g$ being integrable over $[0, 1]$, we observe from* (11) *that the variance satisfies $\sigma_G^2(g = 0) = 0$ with $\sigma_G^2(g) \sim (T_H(-\ln g))^{-1}$ as $g \to 0$. In Figure 6, σ_G is exemplified for $A = 1$.*

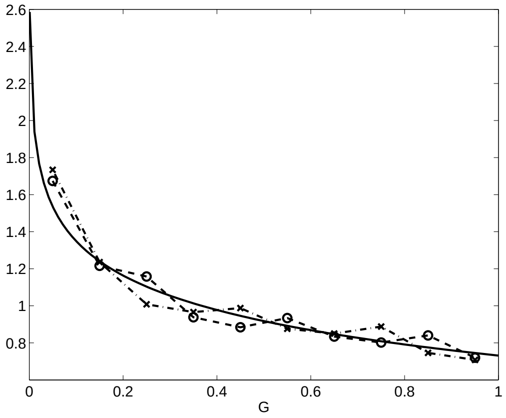


Figure 7: Stationary distribution p_{S_G} (–) vs numerical computed distributions for G_t^ϵ, $\epsilon = 1$ (x-.) and G_t^0 (o- -).

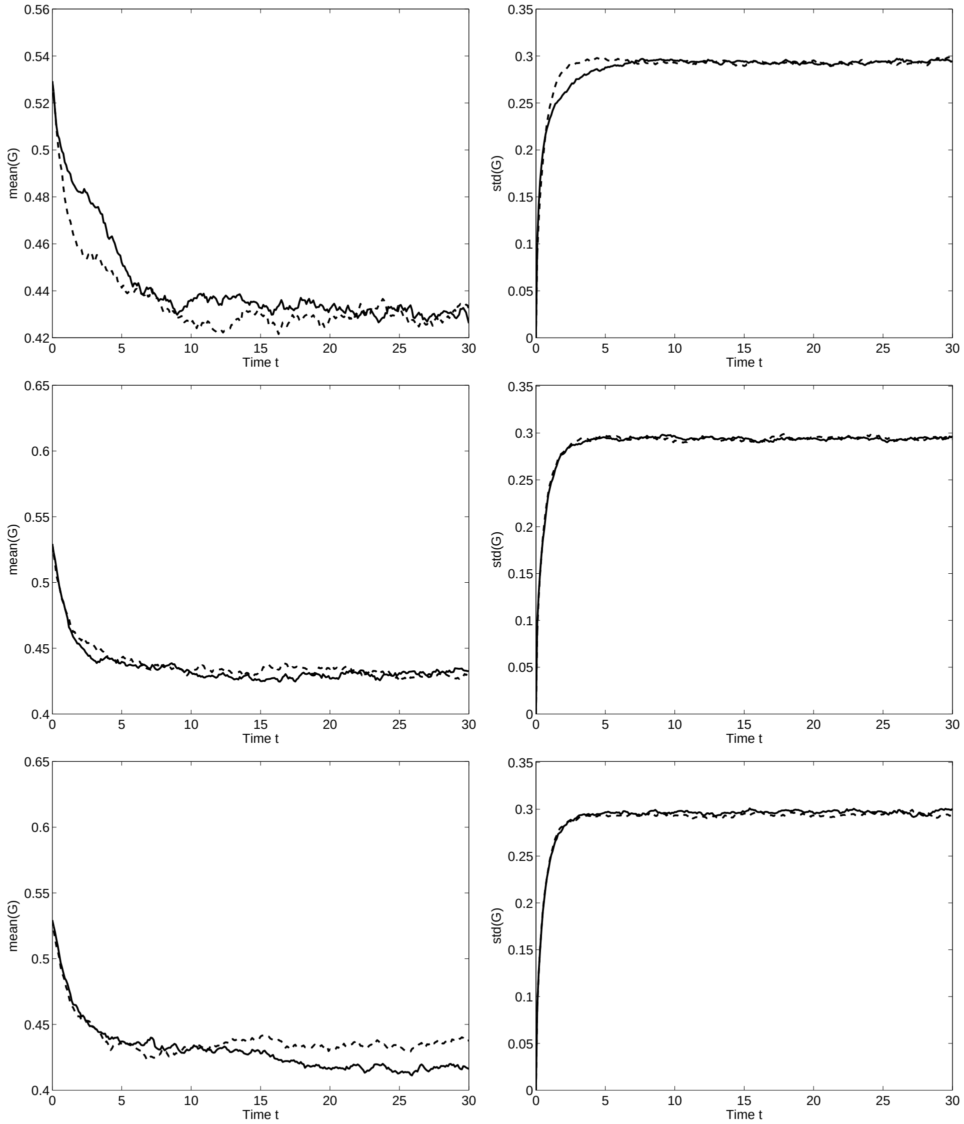


Figure 8: Time development of mean values (left) and standard deviations (right) of G_t^ϵ (–) and G_t^0 (:) for $\epsilon = 1, 0.1, 0.01$ (from top to bottom).

A numerical simulation yields the stationary distributions of the energy process G_t^ϵ, $\epsilon = 1$ and the limit process G_t^0 that are plotted against the theoretical stationary distribution p_{S_G} in Figure 7. The temporal evolution of the mean value and the standard deviation of the two energy processes is visualized in Figure 8, where ϵ is chosen as $\epsilon = 1$, 0.1, 0.01. For large ϵ the decay in the beginning differs significantly, before the final behavior of the processes is driven by the standard noise of Monte-Carlo simulations.

5 Distributions of Process Functionals

An important issue for the quality assessment of fabrics is the distribution of fiber length that lies in a prescribed domain, since this information yields the weight distribution in the physical space and thus gives insight into the structure of the nonwoven material, i.e. holes, thinning, swelling. In the context of stochastic processes the fiber length distribution can be associated with the time distribution the process stays in a certain domain. In the following we perform a numerical study of such functionals of the process.

The "time" spent in a domain D of the (r, β)-phase space is described by the distribution of the random variable $I = \int_{t_0}^{T} \chi_D(r_t, \beta_t)\, \mathrm{d}t$ for fixed T where χ_D is the characteristic function of D. Alternatively for domains given by the energy functional $G = e^{-H}$, e.g. $D = D_g = \{(r, \beta)|\ G(r, \beta) < g\}$, we can also use the approximate equations for G_t^0 to determine an approximation I_G for I with $I_G = \int_{t_0}^{T} \chi_{[0,g]}(G_t^0)\, \mathrm{d}t$.

Remark 4 *The distribution of the above functionals can in principle be determined by solving a related partial differential equation to obtain the characteristic function of I. The distribution of I is then computed using the inverse Fourier transform, see [7]. However, for the nonlinear processes considered here there is no explicit solution of these equations, and a direct evaluation of the functionals by a Monte-Carlo method is more straightforward.*

Figure 9 shows the distribution of the functionals I/T and I_G/T with $D = D_g = \{(r, \beta)|\ G(r, \beta) < g\}$ for initial values $G_0 = 0.53$, $t_0 = 0$, $g = 0.3$ and final time $T = 40$, 200, 400 using the $(r_t^\epsilon, \beta_t^\epsilon)$-process with $\epsilon = 1$ and the G_t^0-process respectively. Obviously, in these cases evaluating the functionals with the limit G_t^0-process gives a good approximation of the true value.

Remark 5 *For large times T, starting with the stationary distribution, the distribution of I_G is governed by the ergodic theorem: the distribution of I_G tends towards a δ-distribution at the value $P(D_g) := \int_0^g p_{S_G}(g')\mathrm{d}g'$:*

$$\lim_{T\to\infty} \frac{1}{T} \int_{t_0}^{t_0+T} \chi_{[0,g]}(G_t^0)\, \mathrm{d}t = P(D_g).$$

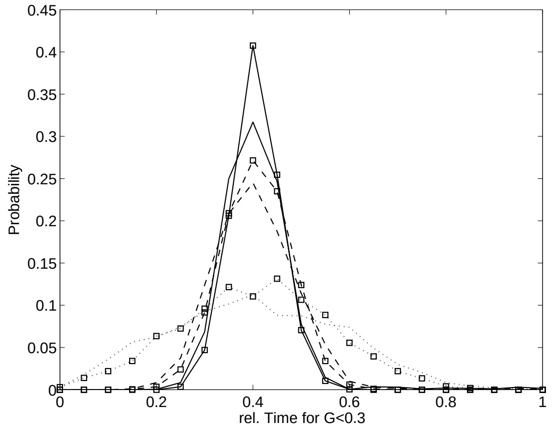


Figure 9: Probability distribution of time spent in D_g, $g = 0.3$, $P(D_g) = 0.39$ using the $(r_t^\epsilon, \beta_t^\epsilon)$-process, $\epsilon = 1$ (line) and G_t^0-process (line & marker) for $T = 40$ (:), 200 (- -), 400 (–).

6 Conclusion and Outlook

By presenting a new stochastic model for the lay-down of fibers, this paper sets the theoretical basis for further investigations of the production process of nonwovens. Thereby, we have determined the associated Kolmogoroff equation and stationary solution of the model and derived the corresponding energy process with drift and variance coefficients by help of stochastic averaging. The limit energy process enables the simple computation of probability distributions of process functionals, e.g. fiber length distribution, that are helpful for the quality assessment of nonwoven materials.

The application of our theoretical results on the industrial process requires the extension of the model with regard to an anisotropic lay-down process and a moving conveyor belt. This generalization will lead to a matrix-valued drive function and an additional drift (transport) term in the (ξ, α)-system. The practical relevance of the model has to be guaranteed by the identification of the parameters, i.e. drive and noise amplitude. Therefore, appropriate validation data will be generated by the simulation of the complete physical production process. Apart from the practical application, the theoretical analysis of the solution of the degenerate Fokker-Planck equations with suitable boundary conditions for the (ξ_t, α_t) or (r_t, β_t) as well as for the limit energy process G_t^0 is also a point of interest that is left to future work.

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