STEERING OF ELECTROSPUN NANOFIBERS WITH ELECTROSTATIC FORCES

[1]ENIKO T. ENIKOV, [2]RUDOLF KYSELICA

Aerospace and Mechanical Engineering Department, University of Arizona
E-mail: [1]enikov@email.arizona.edu, [2]rkyselica@email.arizona.edu

Abstract - Electrospinning is a process of producing sub-micron fibers from polymer solutions utilizing electrostatic forces. In traditional electrospinning process, the resulting fibers form a pseudo-random pattern on the collector electrode. In this paper we present a novel method for controlling the fiber deposition location using dynamically-controller electrostatic forces. It has been shown that under proper amplitude and frequency excitation, the fibers can be deposited in elliptical and linear patterns with various dimensions. A mathematical model describing the deposition process is used to estimate important physical parameters governing the deposition process.

Index Terms - Electrospinning, electrostatic control, fiber orientation.

I. INTRODUCTION

Electrospinning process is becoming a popular process for producing sub-micron nano-fibers [1]-[3]. The underling fiber extrusion process is well known [1] and relies on application of electrostatic force exceeding the surface tension of the polymer solution. As a result, a continuous jet forms, which undergoes simultaneous stretching and drying as it travels to the collector. In a traditional electrospinning process, the fibers land on a flat collector surface, forming a matt with many randomly oriented fibers. Randomly electrospun nanofibers have been explored as templates for cellular growth and creation of artificial tissues [4]-[7]. However, in applications such as motor neuron growth and nerve regeneration, it has been shown that bundles of aligned fibers induce directional neurite growth and could be beneficial in creating linear neuronal arrays [6 Google]. Current methods for producing aligned fibers rely on cumbersomerotating mechanical collectors relaying mechanical stretching of the deposited fibers along the tangential direction [8]. This paper reports on the development of a fiber-steering technique using an auxiliary electrostatic field, applied between the nozzle and collector electrodes. In contrast to past efforts using a combination of dynamic fields and rotating collectors [9], the present technique is based on a set of stationary electrodes generating dynamically modulated lateral deflection fields. The subsequent sections of this paper provide details on the materials and parameters used in this study along with a mathematical model used to characterize the fiber deposition and explore the limitations of the present method.

II. MATERIALS AND METHODS

A. Materials

A 5wt% solution of Polyethylene Oxide (PEO) MW 900,000 from Sigma-Aldrich dissolved in di-ionized (DI) water was used for all experiments described in this work. To prepare the polymeric solution, PEO was gradually stirred into a corresponding amount of DI water heated to80°C. The solution was then kept at this temperature while constantly stirred at 120 RPM for the minimum of 8 hours prior to use.

B. Methods

The electrospinning apparatus is shown in Fig. 1. The auxiliary electrodes are held between the nozzle and collector plate by an array of several rectangular frames.To minimize electric field distortion and electric discharge between components, all the structural components of the device were built from electrically non-conductive materials, except for the nozzle, nozzle shield, auxiliary electrodes, and the collector electrode. For nozzle/spinneret, a 2.54 cm long, 20 G stainless steel blunt dispensing tip from CML supplies was used. A conical nozzle shield was used to cover the electric connection on the nozzle so as to keep the electric field symmetrical. Auxiliary electrodes of size 100x10x1mm were cut from a 1mm thick copper sheet and fixed in electrode holder plate. As a collector electrode, ITO (Indium-Tin-Oxide) coated glass slides with a size of 50x75x0.7mm from Delta Technologies were used.

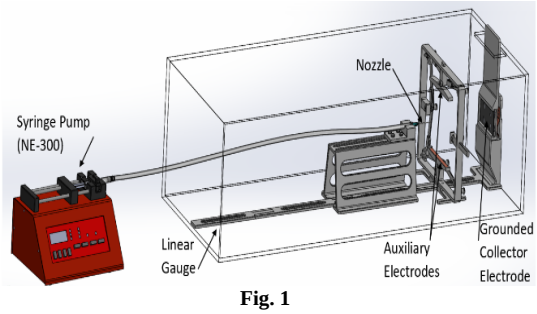

Fig. 1

In the experiments described here, two sets of uxiliary electrodes were used, with different square waves of electric potential applied to each set. These potentials in Volt units are described by equations (1) and (2), respectively

$$U_1 = \frac{U_{amp}}{2}(\mathrm{sgn}(\cos\omega t) + 1) + 660\,, \qquad (1)$$

$$U_2 = \frac{U_{amp}}{2}(\mathrm{sgn}(\cos\omega t + \pi) + 1) + 660, \quad (2)$$

where the amplitude of the forcing function U_{amp}=10kV. The bias of 0.66kV comes from circuit producing the forcing function amplified 1000 times in the amplifier. Frequency of the forcing function is varied from 40 to 250 Hz.

III. ELECTRODYNAMIC STEERING EXPERIMENTS

A. 1D Steering

Electrostatic steering in 1D was demonstrated using only one pair of auxiliary electrodes as previously shown in Fig. 1. When the electric potential functions from (1) and (2) are applied to the two electrodes, the fiber is forced to oscillate in a plane perpendicular to these two electrodes and eventually deposits on the collector electrode in a line-like pattern. This is a result of repulsive/attractive forces generated by the two auxiliary electrodes. The frequency needs to be high enough to prevent a fiber deposition on the low-potential electrode during each cycle. The schematic view of this electrospinning setup with fiber extrusion and deposition is shown in Fig. 2 along with the resulting deposition pattern.

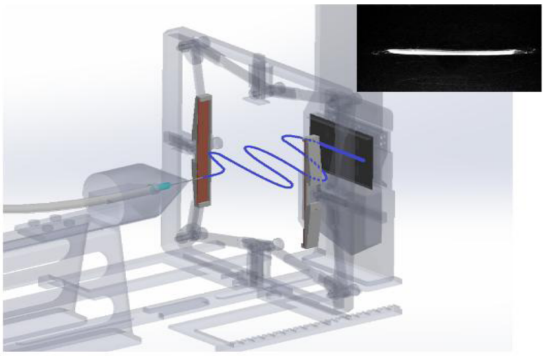

Fig. 2 1D Steering Arrangement of Auxiliary Electrodes and Resulting Linear Pattern

A. 2D Steering

Forced oscillation of the fiber laterally in x-y plane was demonstrated by using two pairs of auxiliary electrodes, rotated by 90° with respect to each other. Additionally the electrode pairs were offset along the axial direction as shown in Fig. 3. Also show is the resulting 2D pattern of the deposited fiber.

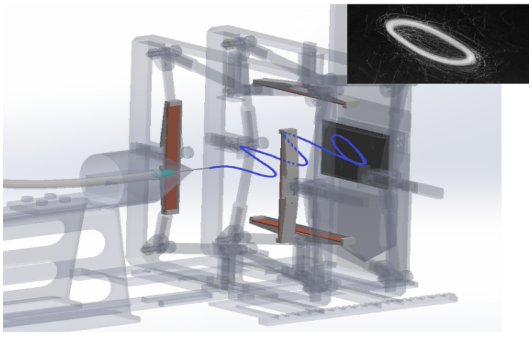

Fig. 3 2D Steering Arrangement of Auxiliary Electrodes and Resulting Elliptical Pattern

As the fiber travels through the region of the first electrode pair(vertical), it is aligned horizontally as previously described in 1D steering section. The second, horizontally aligned, pair of electrodes stretches the fiber in vertical direction. Fiber then deposits in elliptical deposition pattern. Analogous to the 1D fiber steering case, the size of the fiber deposit is dependent on the frequency of the forcing function. This dependency is shown in Fig. 4 and analyzed in the next section of the paper.

IV. MATHEMATICAL MODELLING

In order to analyze the effects of different parameters on the motion of the fiber, a low-order mathematical model of the motion of the fiber was created. The fiber was discretized into 5 charged "beads" endowed with mass and electric charge and connected with each-other via springs and dash-pots. Considering that the PEO nanofiber drying takes place over a distance of just about 45 mm [kys], the fiber inside the auxiliary electrodes was modeled as Kelvin-Voigt solid material. Correspondingly, material properties such as density, Young`s modulus were also derived from published data of solid PEO fibers. Further simplification is the assumption of a diameter which allows the computation of the concentrated mass and charge for each of the beads. The "beads" are restricted to move in planes perpendicular to the axis of the device as illustrated in Fig. 4.

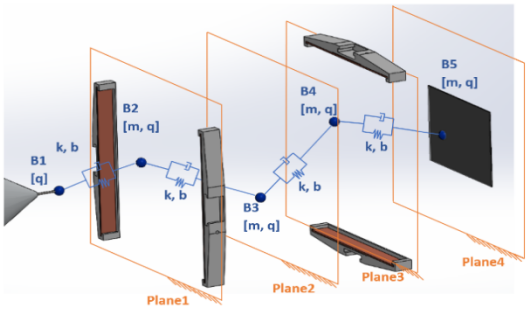

Fig.4 Spring-Mass-Charge Model

The resulting equations of motion are shown in (3).

$$m\ddot{x}_{j,i} + c_{stokes}\dot{x}_{j,i} + c_{struct}\frac{dL_{i,i-1}}{dt}\frac{(x_{j,i}-x_{j,i-1})}{L_{i,i-1}} - c_{struct}\frac{dL_{i,i+1}}{dt}\frac{(x_{j,i}-x_{j,i+1})}{L_{i,i+1}} + k(x_{j,i}-x_{j,i-1})\left(1-\frac{L}{L_{i,i-1}}\right) - k(x_{j,i+1}-x_{j,i})\left(1-\frac{L}{L_{i,i+1}}\right) - \sum_{k=1}^{n}\left(\frac{k_e(\lambda_q L)^2}{L_{i,k}^3}(x_{j,i}-x_{j,k})\right) + F_{i,j} = 0 \quad (3)$$

where $j \in \{1,2\}$ is the direction of motion, $i \in \{1,2..n\}$ is the "bead" number, and $n = 5$ is the number of beads in the model. $L_{i,j}$ is the distance between "beads" i and j, $k_e = 1/4\pi\epsilon_0$, and λ_q is the linear charge density. c_{stokes} and c_{struct} are the Stokes and structural drag and damping coefficients, and k is the linear stiffness of the fiber. The values used in the

model are $m = 1.72 \times 10^{-12}$ kg, $L = 2 \times 10^{-2}$ m, $\lambda_q = 7.49 \times 10^{-8}$ C, $k = 0.0247$ N/m, $c_{stokes} = 2.342 \times 10^{-6}$ N-s/m, and $c_{stokes} = 1 \times 10^{-5}$ N-s/m. The external Coulomb forces $F_{i,j} = L\lambda_q E_{i,j}(t)$ were computed from the electrostatic field $E_{i,j}(t)$, which was obtained via finite element analysis (FEA) for each plane of motion. For a 5-bead model, one "bead" is at the nozzle, one is at the collector, and the remaining three beads occupy three planes. The potentials and electric field distributions in each of these planes is shown in Fig. 5.

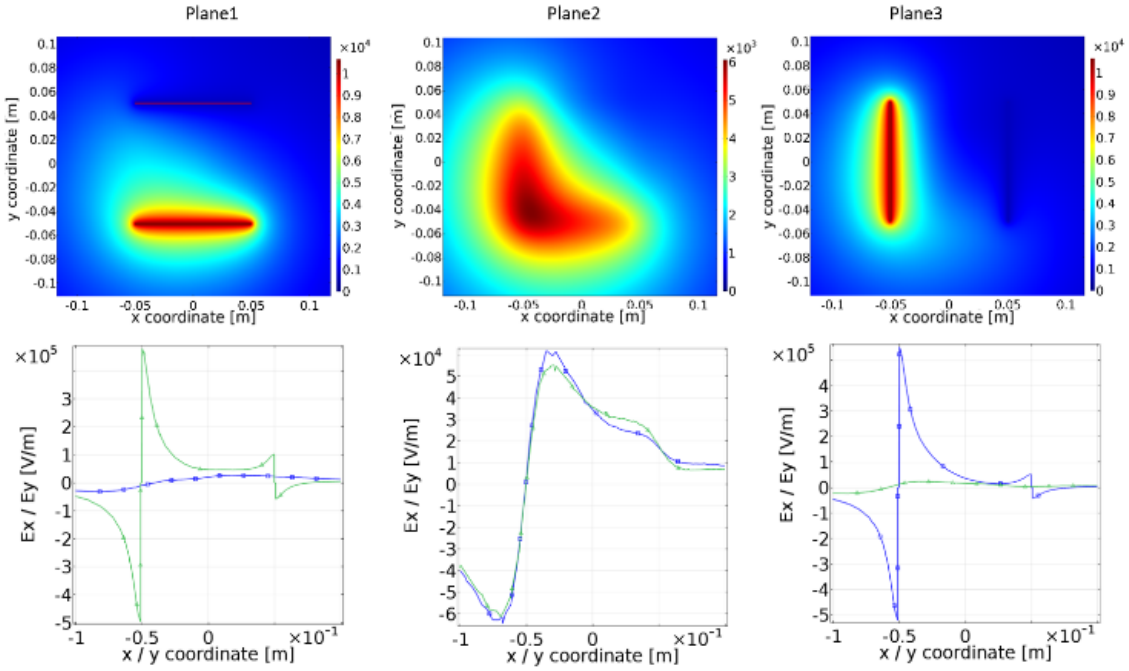

Fig. 5 Electric Potential and Field Distribution During The First Half-Period of Excitation.

Numerical solutions of the model (3) are shown in Fig. 6. By tuning the model parameters to the observed pattern sizes at different frequencies of excitation, it was possible to extract values of the Stokes and drag friction coefficients. The model successfully predicted reduction of the pattern size with increase of excitation frequency, suggesting over-damped system response.

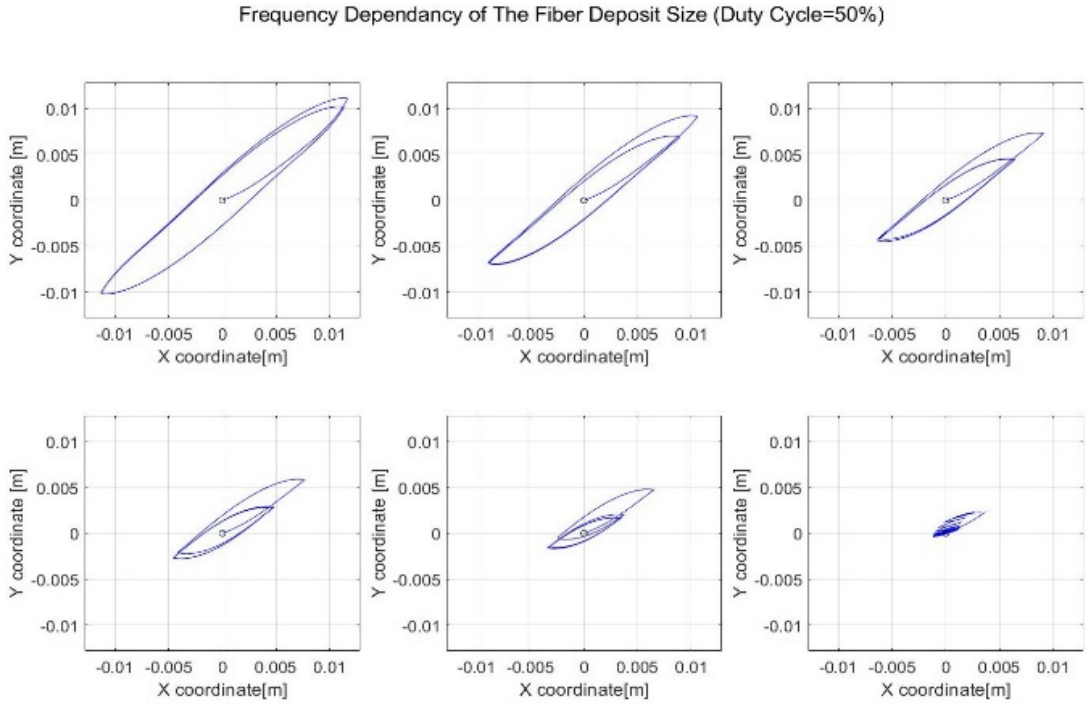

Fig. 6 Fiber Deposition Patterns Predicted by Eqn (3).

Comparison of the experimentally obtained amplitude (defined as the long axis of ellipse) with simulation results from (3) for different frequencies is shown in Fig. 7.

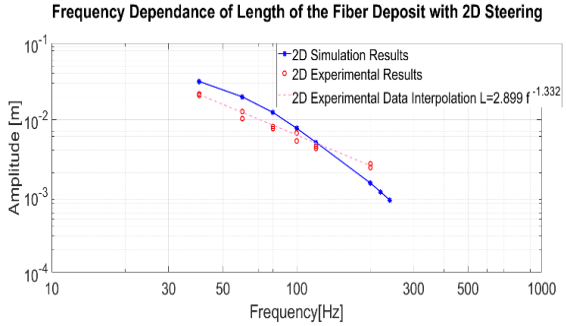

Fig. 7 2D Pattern Size vs Frequency Predicted by Simulation and Experiment

CONCLUSIONS

1D and 2D fiber steering was demonstrated using rectangular voltage waveform applied to a set of auxiliary deflection electrodes. The behavior of the fiber demonstrated over-damped response which is contract to previous reports suggesting negligible air damping [ ]. Despite its simple nature, the model used in this work successfully captured the frequency dependence of the size of linear (1D) and elliptical (2D) patterns.

REFERENCES

[1] D. H. Reneker, A. L. Yarin, "Electrospinning jets and polymer nanofibers," Polymer vol. 49(10) pp. 2387-2425. doi:10.1016/j.polymer.2008.02.002, 2008.

[2] N. Bhardwaj, S. C. Kundu, Electrospinning: A fascinating fiber fabricationtechnique, Biotechnology Advances vol28 pp. 325 - 347. doi:10.1016/j.biotechadv.2010.01.004, 2010.

[3] J. Doshi, D. H. Reneker, Electrospinning process and applications of electrospun fibers, Journal of Electrostatics vol. 35 (2) pp.151- 160. doi:10.1016/0304-3886(95)00041-8, 1995.

[4] Swartz, D., Russell, J., and Andreadis, S., "Engineeringof fibrin-based functional and implantable smalldiameterblood vessels". American Journal of PhysiologyHeart and CirculatoryPhysiology v.288, pp. 1451–1460, 2005.

[5] G. Matsumura, N.Hibino, Y.Ikada, H.Kurosawa, and T. Shinoka, "Successful application of tissue engineered vascular autografts: clinical experience". Biomaterialsvol24, pp. 2303–2308, 2003.

[6] B.Harley, A. Hastings, I. Yannas, and A. Sannino, "Fabricating tubular scaffolds with a radial pore size gradientby a spinning technique". Biomaterials vol. 27, pp. 866–874, 2006

[7] C. Xu, R.Inai, M.Kotaki, and S. Ramakrishna, "Aligned biodegradable nanofibrous structure: a potentialscaffold for blood vessel engineering". Biomaterials vol. 25,pp. 877–886, 2004.

[8] C. Gertz, M. Leach, L. Birrell, D. Martin, E. Feldman, and J. Correy, "Accelerated neuritogenesis and maturation of primary spinal motor neurons in response to nanofibers." Developmental neurobiology vol. 708 pp. 589-603, 2010.

[9] P. Katta, M. Alessandro, R. D. Ramsier, G. G. Chase, Continuous electrospinningof aligned polymer nanofibers onto a wire drum collector,NanoLetters vol. 4, pp 2215–2218 doi:10.1021/nl0486158, 2004.

★★★