A METHOD FOR SIMULATING DNA ELECTROPHORESIS IN ELECTRICALLY INSULATING MICROFLUIDIC AND NANOFLUIDIC GEOMETRIES

J. Cho and K. D. Dorfman

Chemical Engineering and Materials Science, University of Minnesota, USA

ABSTRACT

We present a hybrid boundary element method (BEM)/Brownian dynamics (BD) algorithm for simulating DNA electrophoresis in an inhomogeneous electric field. The accuracy of the method is demonstrated by studying the collision with a finite-sized cylindrical post, where the exact solution of the electric field is known.

KEYWORDS: DNA, Electrophoresis, Simulation, Modeling

INTRODUCTION

Virtually all microfluidic and nanofluidic devices are fabricated using electrically insulating materials (silicon, glass, or plastics), and their relatively complex features can lead to strongly inhomogeneous electric fields. We have developed a new method for simulating DNA electrophoresis in these devices, based on a mixed boundary element method/Brownian dynamics (BEM/BD) approach. By and large, most simulations of DNA electrophoresis in these devices replace the true electric field with a uniform one [1]. Although these simulations are fast, they may neglect important effects of the curved field lines on the DNA dynamics [2]. While it is possible to merge a finite element solution for the electric field with the BD simulation [3], the implementation is non-trivial. Our approach is straightforward and computationally efficient, opening up a new route for simulating DNA electrophoresis in the vast array of devices currently being explored in the microfluidics and nanofluidics community. Moreover, the BEM method is ideally suited for considering active nanodevices with dynamically changing shapes and electric fields.

THEORY

The boundary element method entails meshing the boundaries of the device, rather than the interior. Each element represents a point source solution to the Laplace equation, and the strength of these sources is adjusted such that the system satisfies a surface integral form of the Laplace equation. The boundary element method is naturally suited for microfluidic devices, as the transport in these devices is often determined by the shape of the boundaries. The DNA is represented by the bead-spring model proposed by Doyle and coworkers (see, for example, [3]). The electric field acting on each bead is computed by an appropriate surface integral of the point sources. While the calculation is straightforward far from the surfaces, non-uniform electric field solutions become quite challenging as the DNA approaches the surface [3]. The boundary element method is able to produce very accurate electric fields near the surface by a shift in the numerical method [4], thereby allowing us to capture the dynamics of the DNA without requiring a fine mesh. The electric field calculations are relatively expensive, but one can retain
sufficient accuracy by updating the electric field only after a bead has moved over its radius.

RESULTS AND DISCUSSION

To demonstrate the accuracy of our method, we studied the collision of a large DNA molecule with a single insulating post. As the electric field distribution for such a geometry is known [2,3], it provides an ideal test bed for our BEM/BD method. Figure 1 depicts several snapshots of simulations of the DNA molecule colliding with the post using the exact electric field distribution around an isolated cylinder and the BEM solution for the electric field. Both simulations use the same seed value for the random number generator, and thus should furnish identical results. As seen in Figure 1, the BEM/BD simulation is indeed indistinguishable from the BD simulation that uses the exact solution for the electric field. Moreover, as seen in Figure 2, the center-of-mass trajectories are also essentially identical and agree with experiments. These data were obtained by calculating the electric field at every time step.

Figure 1. Snapshots of simulations of the collision of a DNA molecule with a micron-scale post. (a) BEM solution. (b) Exact electric field. The DNA trajectories are indistinguishable, indicating that the BEM method provides adequate spatial resolution for the electric field. The time is in dimensionless BD time (scaled with the friction coefficient, spring length and thermal energy).
CONCLUSIONS

In summary, we have presented a robust method for simulating DNA electrophoresis in an inhomogeneous electric field. We anticipate that this method will prove useful for engineering new DNA analysis devices in plastics, silicon and glass.

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REFERENCES