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Transport of Brownian particles in a deformable tube

Xiao-qun Huang, Peng Deng, Bao-quan Ai *

Laboratory of Quantum Information Technology, ICMP and SPTE, South China Normal University, 510006 Guangzhou, China

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ABSTRACT

Directed transport of Brownian particles in a deformable two-dimensional tube is investigated in the presence of asymmetric unbiased fluctuations. It is found that the current can be enhanced by choosing appropriate noise intensity and deformation. There exists a value of deformation at which the current takes its maximum. For small deformable parameter, transport is dominated by noise intensity, and for very large deformable parameter, transport is dominated by deformation. The competition between the deformation and the asymmetric driving forces will induce rich phenomena in transport.

1. Introduction

The problem of transport induced by zero-mean nonequilibrium fluctuations has attracted much interest in the nonlinear systems. This comes from the desire of understanding molecular motors [1], nanoscale friction [2], surface smoothening [3], coupled Josephson junctions [4], optical ratchets and directed motion of laser cooled atoms [5], and mass separation and trapping schemes at microscale [6]. In these systems, the directed Brownian motion of particles is generated by unbiased nonequilibrium perturbations, deterministic and random alike, together with a spatial or temporal symmetry breaking. Several typical models have been proposed: rocking ratchets [7], flashing ratchets [8], diffusion ratchets [9], correlation ratchets [10]. The ratchet setup demands three principal ingredients [11] which are nonlinearity, asymmetry and non-equilibrium driving force.

Most studies have revolved around the energy barrier. When particles pass from one well to the other, the nature of the barrier relies on which thermodynamic potential varies, and their presence exerts a great influence on the dynamics of the system. However, in some cases, such as soft condensed matter and biology systems, one should consider the entropic barriers. The entropic barriers may appear when approaching the exact dynamics by coarsening the description of a complex system. Reguera and coworkers [12] used the mesoscopic nonequilibrium thermodynamics theory to derive the general kinetic equation for a system in a domain of irregular geometry, in which the presence of the boundaries induces an entropic barrier. In their recent work [13], they studied the current and diffusion of Brownian particle in a symmetric channel with a biased external force.

Most of the studies have referred to the regular tube. However, in the real physical systems, the shape of the tube can deviate from the standard (sinusoidal) one, and this may affect strongly the transport properties of the systems. The effects of the shape for deformable tube on directed transport are still unknown. In the present paper, we study the directed transport of Brownian particles in an asymmetric deformable tube in the presence of unbiased forces. We emphasize finding how the deformation affects the directed transport.

* Corresponding author.
E-mail addresses: aibq@scnu.edu.cn, aibq@hotmail.com (B.-q. Ai).

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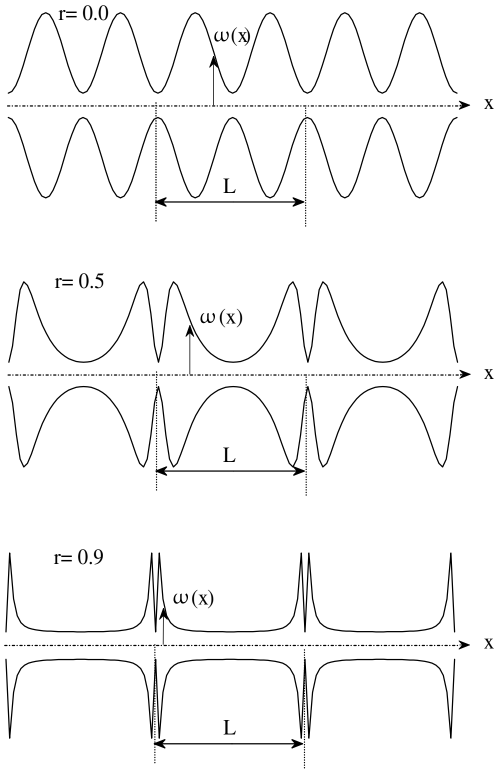

Fig. 1. Schematic diagram of a tube with periodicity L for different values of deformable parameter r. The shape is described by the radius of the tube $\omega(x)$ Eq. (4). $a = 1/2\pi$, $b = 0.3/2\pi$.

2. Model and methods

We consider Brownian particles moving in the asymmetric deformable tube in the presence of temporally asymmetric force. Its overdamped dynamics can be described by the following Langevin equations in the dimensionless form [13]:

$$\eta \frac{\mathrm{d}x}{\mathrm{d}t} = F(t) + \sqrt{\eta D}\xi_x(t), \tag{1}$$

$$\eta \frac{\mathrm{d}y}{\mathrm{d}t} = \sqrt{\eta D}\xi_y(t), \tag{2}$$

where x, y are the two-dimensional coordinates, t is the time, and η is the friction coefficient of the particle. For simplicity, we set $\eta = 1$ throughout the work. The noise intensity $D = k_B T$, k_B is the Boltzmann constant, T is the temperature. $\xi_{x,y}(t)$ presents the Gaussian white noises with zero mean and correlation function: $\langle \xi_i(t)\xi_j(t')\rangle = 2\delta_{i,j}\delta(t-t')$ for $i, j = x, y$. $\langle \cdots \rangle$ denotes an ensemble average over the distribution of noise. $\delta(t)$ is the Dirac delta function. The reflecting boundary conditions ensure the confinement of the dynamics within the tube. $F(t)$ is the temporally asymmetric unbiased force with zero mean over the period and given by Chialvo and Millonas [14]

$$\begin{aligned} F(t) &= \frac{1+\epsilon}{1-\epsilon}F_0 \quad \left(n\tau \le t < n\tau + \frac{1}{2}\tau(1-\epsilon)\right), \\ &= -F_0 \quad \left(n\tau + \frac{1}{2}\tau(1-\epsilon) \le t < (n+1)\tau\right), \end{aligned} \tag{3}$$

where ϵ characterizes the temporal asymmetry in the periodic force, τ is the period of the unbiased force and F_0 is its magnitude.

The shape of the tube is described by (see Fig. 1)

$$\omega(x) = a\frac{(1-r^2)^2[1-\cos(2\pi x)]}{[1+r^2+2r\cos(\pi x)]^2} + b, \tag{4}$$

where a is the parameter that controls the slope of the tube, b determines the half width at the bottleneck and r is the deformable parameter. The degree of the deformation increases with $|r|$. The tube reduces to the simply sinusoidal tube for