Physica A 439 (2015) 1–6

Contents lists available at ScienceDirect

Physica A

journal homepage: www.elsevier.com/locate/physa

Absolute negative mobility of interacting Brownian particles

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HIGHLIGHTS

- Both the interaction and the thermal fluctuations play key roles in the ANM.
- In the presence of the interaction, the ANM may appear in multiple regions.
- The weak interaction facilitates the ANM while the strong interaction destroys the ANM.

ARTICLE INFO

Article history:
Received 6 February 2015
Received in revised form 17 May 2015
Available online 29 July 2015

Keywords:
Interacting Brownian particles
Absolute negative mobility

ABSTRACT

Transport of interacting Brownian particles in a periodic potential is investigated in the presence of an ac force and a dc force. From Brownian dynamic simulations, we find that both the interaction between particles and the thermal fluctuations play key roles in the absolute negative mobility (the particle noisily moves backwards against a small constant bias). When no the interaction acts, there is only one region where the absolute negative mobility occurs. In the presence of the interaction, the absolute negative mobility may appear in multiple regions. The weak interaction can be helpful for the absolute negative mobility, while the strong interaction has a destructive impact on it.

1. Introduction

Noise-induced transports play a crucial role in many processes from physical and biological to social systems. In these systems directed Brownian motion of particles is induced by nonequilibrium noise in the absence of any net macroscopic forces and potential gradients [1,2]. Brownian ratchets have been proposed to model the unidirectional motion driven by zero-mean nonequilibrium fluctuations. Broadly speaking, there are four types of Brownian ratchet models: rocking ratchets [3,4], flashing ratchets [5–7], correlation ratchets [8–11], and entropic ratchets [12,13]. The nonequilibrium fluctuations in these systems can induce some peculiar phenomena, and the absolute negative mobility is one of the most novel phenomena. When a system at rest is perturbed by a constant external force, we expect that it responds by moving in the direction of that force. The rather surprising opposite behavior in the form of a permanent motion against a (not too large) static force of whatever direction is called absolute negative mobility.

The absolute negative mobility in the ratchet systems has received much attention [14–20]. Eichhorn and coworkers [14] considered a single Brownian particle in a spatially symmetric, periodic system far from thermal equilibrium and found that the average particle velocity is negative for positive force and positive for negative force. In the one-dimensional symmetric periodic system, the interplay between the ac driving force and the thermal equilibrium fluctuations can induce absolute negative mobility [15]. In the same system, multiple current reversals were observed in an asymmetrical potential [16].

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http://dx.doi.org/10.1016/j.physa.2015.06.050
0378-4371/

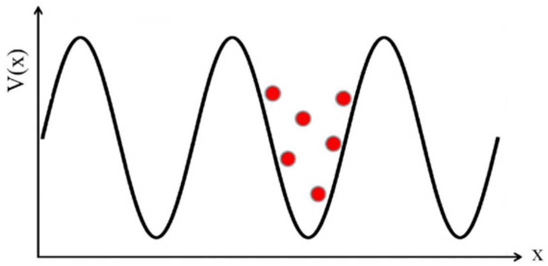

Fig. 1. (Color online) Scheme of interacting Brownian particles in one-dimensional spatially symmetric periodic potential.

Hänggi and coworkers [17] found that asymmetry in shape can cause absolute negative mobility. In addition, the colored thermal fluctuations [18], white Poissonian noise [19] can also induce absolute negative mobility. In a corrugated channel, elliptic Janus particles can show giant negative mobility [20]. In terms of electric transport, negative conductances or even absolute negative conductances have been theoretically and experimentally investigated in the Josephson junctions [21–24]. Except single Brownian particle, coupled Brownian motors have been discussed before in the literature [25–27].

Speer and coworkers [28] found that the origin of quite unusual transport properties is a subtle interplay between the stability of coexisting attractors, noise-induced metastability, and transient chaos. The physical mechanisms that a single, classical Brownian particle occur absolute negative mobility and multiple current reversals in a periodic, symmetric, two-dimensional potential landscape have been demonstrated [29,30].

Most studies of absolute negative mobility have focused on zero interaction between particles. However, the interaction between particles may play the key role in the transport. Therefore, it is necessary to study the effect of the interaction on absolute negative mobility. In this paper, we extend the previous work [15] from zero interaction to the finite interaction. We put the emphasis on finding how the interaction between particles affects absolute negative mobility. Li and coworkers [31] put forward that the inertia of the particle is an ingredient for the appearance of the negative mobility phenomenon in thermal-inertial ratchet system. For sufficiently narrow pores or sufficient large drives, inertia comes into play by enhancing the blocking action of the channel bottlenecks [32,33]. As the inertial effects play a crucial role for anomalous transport feature, we consider under-damped motion of Brownian particles.

2. Model and methods

We consider under-damped dynamics of a set of n interacting Brownian particles that moving in a one-dimensional periodic potential as shown in Fig. 1. The particles are subjected to an unbiased external force $A\cos(\Omega t)$ and a static force F. The corresponding dynamics of the system can be described by the following inertial Langevin equation [15]:

$$M\ddot{x}_i + \Gamma\dot{x}_i = -V'(x_i) + A\cos(\Omega t) + F + \sqrt{2\Gamma k_B T}\xi^{(i)}(t) + \sum_{j\neq i} k(x_j - x_i), \tag{1}$$

where $i = 1, 2, \ldots, n$. The dot and the prime denote a differentiation with respect to time t and the particle's space position x_i, respectively. The last term in Eq. (1) is assumed to derive from an interaction potential. M is the mass of a Brownian particle, Γ the friction coefficient, k the attractive strength between particles, k_B the Boltzmann constant, and T the temperature. A and Ω are the amplitude and the frequency of the ac force, respectively. Thermal equilibrium fluctuations are modeled by zero-mean, Gaussian white noise $\xi(t)$, with the following relations:

$$\langle \xi^{(i)}(t)\rangle = 0, \qquad \langle \xi^{(i)}(t)\xi^{(j)}(t')\rangle = \delta_{ij}\delta(t-t'). \tag{2}$$

The spatial periodic potential is symmetric and can be represented by

$$V(x) = \triangle V \sin\left(\frac{2\pi x}{L}\right), \tag{3}$$

where ΔV is the potential height and L is the period. For the sake of simplicity, we rewrite Eq. (1) in dimensionless form:

$$\ddot{\hat{x}}_i + \gamma\dot{\hat{x}}_i = -\hat{V}'(\hat{x}) + a\cos(\omega\hat{t}) + f + \sqrt{2\gamma D_0}\hat{\xi}^{(i)}(\hat{t}) + \sum_{j\neq i}\hat{k}(\hat{x}_j - \hat{x}_i), \tag{4}$$

where $\hat{x} = \frac{x}{L}$ and $\hat{t} = \frac{t}{\tau_0}$ with $\tau_0 = L\sqrt{\frac{M}{\Delta V}}$. So $\dot{x} = \frac{L}{\tau_0}\dot{\hat{x}}$, $\ddot{x} = \frac{L}{\tau_0^2}\ddot{\hat{x}}$, and $V(x) = \Delta V\hat{V}(\hat{x})$. Other dimensionless parameters are the amplitude $a = \frac{AL}{\Delta V}$, the load $f = \frac{FL}{\Delta V}$, the dimensionless attractive strength $\hat{k} = \frac{kL^2}{\Delta V}$, the frequency $\omega = \Omega\tau_0$, and the noise intensity $D_0 = \frac{k_B T}{\Delta V}$. In the following discussion, we will use dimensionless variables and omit all the "hat" occurring in Eq. (4).