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Feedback control of an ensemble of self-propelled particles

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HIGHLIGHTS

- We propose a new feedback control scheme based on the direction of the self-propelled speed.
- The directed transport can be improved significantly by increasing the feedback control strength.
- The environment fluctuations play important roles in the transport.
- The transport will not be influenced by the feedback control for large ensembles of self-propelled particles.

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ABSTRACT

Rectified transport of self-propelled particles in an asymmetric period potential is numerically investigated by employing a feedback control protocol. The feedback control is switched on and off depending on the direction of the self-propelled speed. It is found that the direction of the transport is determined by the asymmetry of the potential and the feedback control strength. In the presence of feedback control, the directed transport can be improved significantly by increasing the feedback control strength under appropriate conditions. For large ensembles of particles, however, the feedback control will not obviously affect the transport of self-propelled particles. The present studies may be relevant to some applications in biology and nanotechnology, and provide the predicting results in experiments of active particles.

1. Introduction

Brownian motion in random environment is a long-studying issue in nonequilibrium statical physics. In particular, the rectifying motion of Brownian particles in periodic structures has been investigated extensively due to its importance in theoretical and practical implications [1,2]. Some typical ratchets have been proposed to study the directed transport induced by zero-mean nonequilibrium fluctuations, and they are: rocking ratchets [3,4], flashing ratchets [5,6], correlation ratchets [7–9], and entropic ratchets [10,11]. Additionally, active ratchets, active Brownian particles instead of passive particles in a periodic structure, were also studied in recent years [12–15]. In particular, much attention has been attracted in the transport of swimming bacteria in the presence of an array of asymmetric barriers [16–18]. In most studies on energy ratchets, the switching of the potential is periodically or randomly regardless of the state of the system, and these ratchets are usually called "open-loop" ratchets.

In 2004, Cao and coworkers [19] introduced a flashing ratchet with feedback control ("close-loop" ratchets), where the potential turned on and off depending on the position of the particles with the aim of maximizing the instantaneous

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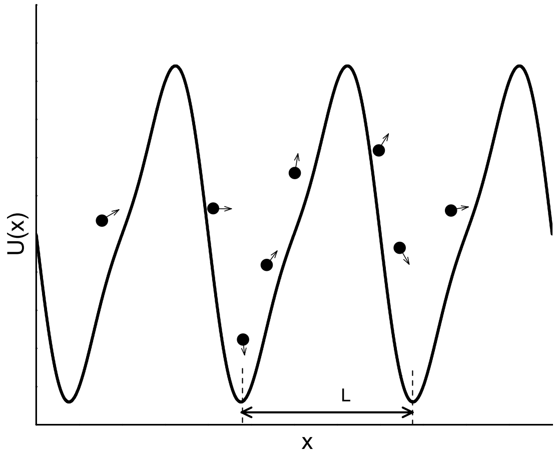

Fig. 1. The asymmetric potential with periodicity L. $U(x) = -U_0[\sin(\frac{2\pi}{L}x) + \frac{\Delta}{4}\sin(\frac{4\pi}{L}x)]$. U_0 is amplitude of the potential and Δ controls the asymmetry of the potential. The black balls represent the self-propelled particles and the arrows show their directions of the self-propelled speed.

velocity (MIV) of the particles. Since then, feedback ratchets have attracted growing attention because of its better rectifying performance than "open-loop" ratchets. Threshold feedback protocol [20] was then proposed for preventing the system with a large number of particles trapping in waiting for fluctuations. In realistic systems, there exists a time delay in the process of the collection, transmission, processing of the information. Researchers [21–26] investigated the effects of time-delayed feedback control on the transport characteristics. It was found that a small time delay reduced the benefit of feedback control since the decorrelation of the used information while a large time delay could improve the performance of the feedback control compared to the nondelayed feedback ratchet in the case of large ensembles of particles [21]. Some other schemes were proposed for modeling better or more realistic feedback implementations of the ratchets. For instance, Craig and coworkers [27] introduced a feedback strategy of maximizing net displacement (MND) of the particles, where the potential was turned on and off based on the expected displacement. Hennig [28] considered a feedback strategy where the control function played a key role on the tuning of the transport. In 2008, Lopez and coworkers [29] realized an experimental feedback ratchet with small numbers of microbeads in water using an optical line trap, and found the observed results being in good agreement with theory predictions.

All particles in the previous studies on feedback control are passive particles. In this work we extend the study of feedback ratchets to the case of self-propelled particles. Because of the self-propulsion of the particles, some striking transport behaviors are significantly different from passive particles. In the following, we will propose a feedback control scheme, where we regulate the direction of the self-propelled speed, and find that the rectification is greatly improved in the presence of the feedback control.

2. Model and methods

We consider an ensemble consisting of N self-propelled particles in an asymmetric periodic potential $U(x)$ of period L as shown in Fig. 1. In the overdamped limit, the dynamics of the self-propelled particles can be described by the following Langevin equations in the dimensionless form,

$$\dot{x}_i(t) = v_0 \cos\theta_i - \mu U'(x_i) + \xi_i(t), \tag{1}$$

$$\dot{\theta}_i(t) = \tau\alpha(t) + \eta_i(t); \quad i = 1, \ldots, N, \tag{2}$$

where $x_i(t)$ is the position of particle i, $\theta_i(t)$ and v_0 are the self-propelled angle and velocity, respectively. μ is the mobility and $U'(x_i) = \frac{\partial U(x_i)}{\partial x_i}$. $\xi_i(t)$ are Gaussian white noises and satisfy the following relations,

$$\langle \xi_i(t) \rangle = 0, \tag{3}$$

$$\langle \xi_i(t)\xi_j(s) \rangle = 2D_0\delta_{ij}\delta(t-s). \tag{4}$$

The symbol $\langle \ldots \rangle$ denotes an ensemble average over the distribution of the random forces. D_0 is the translational diffusion constant and δ is the Dirac delta function. $\eta_i(t)$ are Gaussian white noises which models the fluctuations of the self-propelled angle θ and satisfy

$$\langle \eta_i(t) \rangle = 0, \tag{5}$$

$$\langle \eta_i(t)\eta_j(s) \rangle = 2D_\theta\delta_{ij}\delta(t-s), \tag{6}$$