Physics Letters A 380 (2016) 3490–3496

Contents lists available at ScienceDirect

Physics Letters A

www.elsevier.com/locate/pla

Flow enhancement of deformable self-driven objects by countercurrent

Takashi Mashiko *, Takashi Fujiwara

Department of Mechanical Engineering, Shizuoka University, Hamamatsu 432-8561, Japan

ARTICLE INFO

Article history:
Received 23 May 2016
Received in revised form 26 August 2016
Accepted 26 August 2016
Available online 31 August 2016
Communicated by C.R. Doering

Keywords:
Transport system
Deformable object
Countercurrent

ABSTRACT

We report numerical simulations of the mixed flows of two groups of deformable self-driven objects. The objects belonging to the group A (B) have drift coefficient $D = D_{\mathrm{A}}$ (D_{B}), where a positive (negative) value of D denotes the rightward (leftward) driving force. For co-current flows ($D_{\mathrm{A}}, D_{\mathrm{B}} > 0$), the result is rather intuitive: the net flow of one group (Q_{A}) increases if the driving force of the other group is stronger than its own driving force (*i.e.*, $D_{\mathrm{B}} > D_{\mathrm{A}}$), and decreases otherwise ($D_{\mathrm{B}} < D_{\mathrm{A}}$). For countercurrent flows ($D_{\mathrm{B}} < 0 < D_{\mathrm{A}}$), however, the result appears paradoxical: the net flow of one group (Q_{A}) can increase with the driving force of the other group ($|D_{\mathrm{B}}|$), and the net flow with a stronger countercurrent can be larger than the net flow with a weaker co-current. This phenomenon is observed only for deformable objects and results from the entanglement of objects, which in turn is caused by their deformability.

1. Introduction

Various multibody systems of self-driven objects have been actively studied in a variety of research fields from physical systems to biological or socio-economic systems, such as the traffic flow of vehicles or pedestrians, bacterial colonies, flocks of birds, crowd panics, or stock market dynamics [1]. In past studies on these multibody systems, each self-driven object was traditionally treated as a point-like particle (with only the minimum excluded-volume effect) or as a rigid body (with the additional effects of size and/or shape). From the viewpoint of statistical physics, however, it is important and intriguing to examine how macroscopic, collective behaviors are affected by the microscopic, individual properties including deformability.

On the basis of this perspective, we proposed the flexible chain-like walker (FCW) model to study the dynamics of multibody systems of deformable self-driven objects [2] and found some peculiar collective behaviors caused by the deformability of individuals [2–4]. For example, in the simplest simulations where FCWs just move around in a square area, they exhibit "spontaneous, irreversible aggregation" [2]. Although there have been various aggregation models such as the diffusion-limited-aggregation (DLA) [5], ballistic deposition [6,7], and the Eden model [8], as well as other models of aggregation of particles [9–13] or of particles aggregates [14–16], all of these models require some adherence for the occurrence and irreversibility of the process. In contrast, the aggregation of FCWs is caused by the deformability of each FCW, and thus observed though no adherence is assumed, which clearly demonstrates the novelty of the mechanism of the process. Another example is the "complete jamming" of FCWs, which is observed when there is a net flow of FCWs [4]. Although there have been many reports of complete jamming (in which each object makes a complete stop and does not move again), all of the reports are on counter flows [17–23], crossing flows [24–28], or on flows through obstacles [29]. The complete jamming of FCWs is the first report for the simplest transport system of unidirectional net flow without obstacles. In this study, we numerically simulate mixed flows of FCWs, wherein another peculiar collective behavior of deformable objects is observed.

2. Model and simulation

The outline of the FCW model is as follows [2,4]. An FCW of length l comprises l serially concatenated particles, which, on a two-dimensional square lattice, occupy l horizontally or vertically adjacent sites. One of the edge particles (the first particle) represents the head of the object and the other (the lth particle) represents the tail. At every time step, the head particle stochastically chooses one of its four nearest-neighbor sites and moves to that site if it is not occupied by another particle. The head particle is followed by the subsequent particles (see Fig. 1, which illustrates the movement of an $l = 5$ FCW). In this study, each FCW always moves unless movement is impossible (*i.e.*, when all four nearest-neighbor sites are occupied, in which case the FCW does not move for that time step), which is realized by repeating the

* Corresponding author.
E-mail address: mashiko.takashi@shizuoka.ac.jp (T. Mashiko).

http://dx.doi.org/10.1016/j.physleta.2016.08.052
0375-9601/

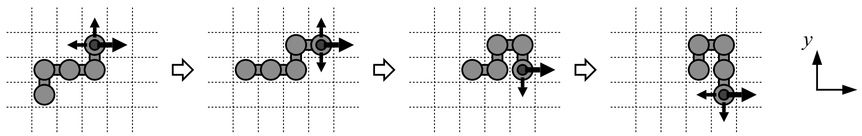

Fig. 1. Typical series of movements of an $l = 5$ FCW. The head particle (represented by the double circle) moves to one of its four nearest-neighbor sites, followed by the subsequent particles. Possible moving directions are indicated by arrows, one of which is the bias direction, represented by the larger arrow ($+x$ direction, corresponding to $D > 0$).

choosing process if an occupied site has been chosen. We should note here that deformability is introduced in each FCW if and only if $l \geq 3$. We also note that the FCW model may be related to polymer physics by further studies such as a recent report of off-lattice simulations [30], in which the head particle can move in any direction and the positions of the subsequent particles can fluctuate, unlike in the present work.

In choosing the direction of motion, we also introduce a "bias", which is denoted by the drift coefficient D ($-1 \leq D \leq 1$), where a positive (negative) value of D means a higher probability of choosing the $+x$ ($-x$) direction, and thus a net collective flow in that direction. Specifically, the probabilities of choosing the $\pm x$ and $\pm y$ directions are given by

$$p_{+x} = D + \frac{1-D}{4}, \quad p_{-x} = p_{+y} = p_{-y} = \frac{1-D}{4} \tag{1}$$

for $D \geq 0$, and

$$p_{-x} = |D| + \frac{1-|D|}{4}, \quad p_{+x} = p_{+y} = p_{-y} = \frac{1-|D|}{4} \tag{2}$$

for $D < 0$.

The simulations are conducted in a channel of L sites in length (x direction) and W sites in width (y direction) with periodic boundaries in both directions. We set $L = 100$ and $W = 20$, unless otherwise noted. At $t = 0$, N objects of length l are placed at random positions in the channel; each object is placed in line with the channel, facing the $+x$ direction (*i.e.*, with its head particle placed rightmost) for $D > 0$, $-x$ direction for $D < 0$, and either $+x$ or $-x$ direction for $D = 0$, where the direction is stochastically chosen on a fifty–fifty basis. All N objects try to move as described above, in a random order which is updated every time step.

To describe the behavior of these objects, we define the following quantities. The density of particles is the ratio of the total number of particles to the number of sites in the channel:

$$\rho = \frac{lN}{LW}. \tag{3}$$

The mean velocity $v(t)$ and the net flow $Q(t)$ are defined as

$$v(t) = \frac{n_+(t) - n_-(t)}{lN}, \tag{4}$$

$$Q(t) = \rho v(t) = \frac{n_+(t) - n_-(t)}{LW}, \tag{5}$$

where $n_\pm(t)$ is the number of particles that have moved in the $\pm x$ direction at time t (note that $n_+(t) + n_-(t) \leq lN$).

In this study, we prepare two groups, A and B, of FCWs. The A and B FCWs have the same length $l_A = l_B$, and the two groups contain the same number of FCWs, so $N_A = N_B$ (and thus, the particle densities are the same: $\rho_A = \rho_B$). The only difference is in their drift coefficients D_A and D_B. Although D_A is fixed at a positive value, D_B can be either positive or negative, to allow both co-current flows ($D_A, D_B > 0$) and countercurrent flows ($D_A > 0 > D_B$).

Furthermore, to demonstrate the effect of deformability, we also simulate rigid objects [4] and compare the results with those of FCWs. A rigid object of length l moves one site in either of the four directions, with its horizontal rod-like shape fixed (*i.e.*, straight in the $\pm x$ directions). The probabilities of choosing the direction are given by Eqs. (1) and (2). Note that the longer the rigid object, the lower the probability of moving in either $+y$ or $-y$ direction when the particle density ρ is high; it is necessary that all l nearest neighbor sites in the chosen $+y$ or $-y$ direction are unoccupied so that the object can actually move in that direction. Therefore, even for $l = 2$, the rigid object is not identical with the FCW (without deformability); the former can move in either $+y$ or $-y$ direction only if both of the two nearest neighbor sites in that direction are unoccupied, resulting in a horizontal position, whereas the latter can move if the nearest neighbor site of the head particle is unoccupied, resulting in a vertical position.

3. Results

The mean velocity $v(t)$ and the net flow $Q(t)$ were generally found to decrease with time and asymptotically approach v_∞ and Q_∞ ($t \to \infty$), respectively. Hereafter, the mean velocity v and the net flow Q refer to these asymptotic values v_∞ and Q_∞, respectively.

Let us first compare the results of simulations for FCWs with those for rigid objects. Figs. 2 and 3 show typical results for rigid objects and FCWs, respectively. In both figures, the mean velocity v_A (left) and the net flow Q_A (right) of group A are plotted as functions of the particle density ρ_A ($= \rho_B$) for $l = 2, 3$, and 5 (from top to bottom). The drift coefficient of group B varies according to $D_B = -0.9, -0.6, -0.3, 0, 0.3, 0.6$, and 0.9, whereas that of group A is fixed at $D_A = 0.6$. Each plotted symbol is obtained by averaging the value over 50 000 time steps in the asymptotic state ($t = 50\,001$ to 100 000) and over at least 100 simulation runs.

We begin by checking the behavior of the rigid objects (Fig. 2), which is rather intuitive. The v_A and Q_A plots have the following features. For $l = 2$ and 3, the shape of the curve for co-current flows ($D_B > 0$) differs from that for countercurrent flows ($D_B < 0$), with a transitional curve for $D_B = 0$, whereas the difference is negligible for $l = 5$. However, the point is that, irrespective of the length l, the curves for $D_B = -0.9, -0.6, -0.3, 0, 0.3, 0.6$, and 0.9 lie in this order from bottom to top, which means that v_A and Q_A increase with D_B. In other words, the flow of rigid objects is larger when accompanied by a co-current than by a countercurrent, by a stronger co-current than by a weaker co-current, and by a weaker countercurrent than by a stronger countercurrent.

We now consider the results for the FCWs (Fig. 3). We see that the behavior qualitatively differs depending on the length l. For $l = 2$, in which case FCWs are not deformable, the plots are similar to those for rigid objects. However, for $l = 3$ and 5, in which case FCWs are deformable, the plots differ significantly from those for $l = 2$. Even for co-current flows ($D_B > 0$), v_A and Q_A drop to zero at relatively low particle density ρ_A. For countercurrent flows ($D_B < 0$), the result is more intriguing. For $l = 2$, the curves for $D_B = -0.3, -0.6$, and -0.9 lie in this order from top to bottom, which means that the net flow (and the mean velocity) decreases as the countercurrent strengthens (the larger $|D_B|$, the smaller Q_A). For $l = 3$, however, the three curves almost overlap, which means that the strength of the countercurrent has little effect on