Aversion of face-to-face situation of pedestrians eases crowding condition

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We conducted numerical simulation for a crowd of pedestrians. Each pedestrian, modeled with three circles, has a shape whose long axis is perpendicular to the anteroposterior axis, and is designed to move fixed destination. The pedestrians have friction at the surface and soft repulsion. In this study, we newly introduced an active rotation which captures psychological effect to evade face-to-face situation. The numerical simulation revealed that active rotation induces fluidization of system leading to higher flux of pedestrian. We further confirmed that this fluidization is due to fragmentation of force chain induced by the active rotation.

I. INTRODUCTION

Active matter is a systems composed of many elements that transduces energy into motion locally. Such active matters are novel type of nonequilibrium system, showing rich dynamical pattern formation. Bird flocks, fish schools, and bacterial colonies are well known examples for active matters [1–4]. The population of human is also considered as active matter and show a variety of pattern formation [5–7].

We here make a model for crowds of pedestrian in high density. It is known that a crowd of pedestrian in high density leads to fatal accidents [8–10]. Such critical situation is due to the formation of force chain within the population, and it leads to stress concentration to small number of pedestrians. Many types of numerical simulation is conducted to understand the behavior of pedestrians in high density [11–13]. In such numerical simulation, a pedestrian can be modeled with active granular particle that follows Newton’s equation of motion, where each individual walks to their fixed destinations [14, 15].

A pedestrian has anisotropy in function and shape: it has frontal part directing their motion, and is wider in the direction perpendicular to the anteroposterior axis [16]. In this study, we newly adopted an active rotation induced by psychological effect. Front direction is preferred direction to move. Interestingly, however, people psychologically avert face-to-face situation each other. We adopt this effect by the active rotation. Our numerical simulation reveals that the coupling between anisotropic shape and active rotation eases crowded condition for pedestrians.

II. SIMULATION SETUP

As shown in Fig. 1, we consider rectangle system, i.e. $L_x = 12$ m and $L_y = 3$ m, and impose the periodic boundary condition on $x$ direction. Each pedestrian has desired direction $e_i = (\pm 1, 0)$, front direction $p_i = (\cos \theta_i, \sin \theta_i)$ ($\theta_i \in [-\pi, \pi]$), and velocity $v_i$. In this study, we model a pedestrian $i$ with central circle whose radius is $\ell_i$, and side circles whose radius is $\ell_i/2$. $\ell_i$ is fixed for each pedestrian and mean of $\ell_i$ is 0.15 m, with $\pm 5\%$ homogeneous

![Figure 1: Schematic illustration of a pedestrian model. Initial condition of numerical simulation. Pedestrians of fixed ratio, $R$, walk positive $x$ direction, whereas the other walk negative $x$ direction. Such desired direction is denoted by $e_i$. Each pedestrian has shape composed of three circles, which has the front direction $p_i$. Central one is twice as large as the other ones. The centers of the side ones situate on the arc of the central one, and perpendicular to $p_i$. Each pedestrian has also the velocity vector $v_i$. The color represents the direction of $p$.](image-url)
One is the physical torque and friction. The surface is assumed to indent each other whose normal distance is \( \delta \), and has relative speed \( v_{\text{rel}} = v_{\text{rel}}^n + v_{\text{rel}}^t \). To incorporate the coulomb friction, we define \( \Xi \) from the relative tangential velocity as

\[
\Xi(t) = \int_{t'=t_s}^{t} v_{\text{rel}}^t(t')dt',
\]

where \( t_s \) is the start time when two surface contact. Then the force acting at the contact point is modeled as

\[
f = F^n \mathbf{n} + F^t \mathbf{t},
\]

where \( \mathbf{n} \) and \( \mathbf{t} \) are outward normal and tangential to the contact surface. Here, \( F^n \mathbf{n} \) is soft core repulsion with viscous damping effect described by

\[
F^n = -k^n \delta - \gamma^n v_{\text{rel}}^n.
\]

\( F^t \mathbf{t} \) describes coulomb friction as

\[
F^t = \begin{cases}
-k^t \Xi - \gamma^t v_{\text{rel}}^t & (|F^t| \leq -\mu F^n) \\
-\mu F^n & (|F^t| > -\mu F^n)
\end{cases}
\]

The physical force \( f_{ij} \) and torque \( N_{ij} \) on pedestrian \( i \) from \( j \) consist of the contact forces between central and side, side to central, and side to side circles represented as red, blue, and green lines in Fig 2(b).

Contact force between central circle on \( i \) from \( j \), \( f_{ij}^c \) is calculated with following way. The distance between the central circles of \( i \) and \( j \), is given by \( d = |r_i - r_j| \). Then, we have \( \mathbf{n} = (n_x, n_y) = (r_j - r_i)/d \), and \( \mathbf{t} = (-n_y, n_x) \), and

\[
\delta = \begin{cases}
0 & (d \geq \ell_i + \ell_j) \\
\ell_i + \ell_j - d & (d < \ell_i + \ell_j)
\end{cases}
\]

The relative velocity is

\[
v_{\text{rel}}^n = (v_i - v_j) \cdot \mathbf{n},
\]

and

\[
v_{\text{rel}}^t = (v_i - v_j) \cdot \mathbf{t} + \ell_i \omega_i + \ell_j \omega_j.
\]

Note that the effect of rotation is also included by \( \ell_i \omega_i \) and \( \ell_j \omega_j \).
The contact force on the central circle of $i$ from the side circle $j$ is calculated in the following manner. Here we exemplify the contact force $f^c_{ij}$, the force on central circle of $j$ from the right circle of $i$. Now, we have $d = |r_i - r_j^r|$, $n = (n_x, n_y) = (r_j^r - r_i)/d$, and $t = (-n_y, n_x)$.

$$\delta = \begin{cases} 0 & (d \geq \ell_i + \ell_j/2) \\ \ell_i/2 + \ell_j/2 - d & (d < \ell_i + \ell_j/2) \end{cases}$$

The relative velocity is now,

$$v^n_{rel} = (v_i - v_j) \cdot n,$$

and

$$v^t_{rel} = (v_i^t - v_j^t) \cdot t + \ell_i \omega_i.$$  

The contact force on the side circle of $i$ from the side circle $j$ is calculated in the following manner. Here we exemplify the contact force $f^s_{ij}$, the force on the left circle of $j$ from the right circle of $i$. Now, we have $d = |r_i^l - r_j^l|$, $n = (n_x, n_y) = (r_j^l - r_i^l)/d$, and $t = (-n_y, n_x)$.

$$\delta = \begin{cases} 0 & (d \geq \ell_i/2 + \ell_j/2) \\ \ell_i/2 + \ell_j/2 - d & (d < \ell_i/2 + \ell_j/2) \end{cases}$$

The relative velocity is now,

$$v^n_{rel} = (v_i^l - v_j^l) \cdot n,$$

and

$$v^t_{rel} = (v_i^l - v_j^l) \cdot t.$$  

Finally we have,

$$f_{ij} = \sum_\alpha f^\alpha_{ij},$$  

where $\alpha$ is 9 possible combination of $c$, $l$ and $r$. We also have

$$N^\text{phy}_{ij} = \sum_\alpha (R_\alpha - r_i) \times f^\alpha_{ij},$$

Here, $f^\text{phy}$ is psychological force affecting only rotation, and defined as

$$f^\text{phy}_{ij} = \begin{cases} B(2r_p - |r_{ji}|) \frac{r_{ji}}{|r_{ji}|} & (|r_{ji}| < 2r_p \land |\Delta \theta_{ij}| > \frac{\pi}{2}) \\ 0 & \text{(otherwise)} \end{cases}$$

Here, we define relative position vector $r_{ji} = r_j - r_i$ as $r_{ji}$.

We mainly used parameters according to prior study. As mentioned the mean of $\ell_i$ is 0.15 m, and distributed in 0.1425-0.1575 m with homogeneous random distribution. $v_0$ is randomly distributed in 0.8-1.2 m/s. $m_i$ is also randomly distributed in 40-70 kg. Other parameters are as follows: $L_x = 12$ m, $L_y = 3$ m, $r_W = 0.1$ m, $\tau = 0.67$ s, $I = 1.0 \text{ kg m}^2$, $k^v = 1.0 \times 10^5 \text{ N/m},$
We measured the number of pedestrian snapshots in denser system (\(T\) boundary at the left and the right in Fig. 3) of current system with parameters: the packing lane formation, avalanche, and clogging. The phase diagram of current model: This situation is almost the same as prior study. Figure 3 shows typically observed behavior of current model: as increase of the psychological repulsion increase effective occupation area, and should enhance clogging.

We analyzed the physical stress in detail to grasp the essential mechanism of fluidization due to the effect of \(B\). We obtained minimum principal stress for each pedestrian \(\sigma_3\), which is essentially compressive stress. The averaged value of the size \(\sigma_3\) is plotted in Fig. 4(a). As seen, \(\sigma_3\) decreases with the increase in \(B\), when the system become fluidized. The snapshots as well as force chain structure obtained to visualize the effect of \(B\). The force chain is reconstructed based on the algorithm proposed by Peters et al. The averaged size of compressive stress \(\sigma_3\) with various parameters \(\phi\) and \(B\) with \(R = 0.5\). (b, c) Typical snapshots in denser system (\(\phi = 0.8\)) and force chain network observed. (c) When \(B = 1000\), i.e. psychological effect is strong, short and localized force chain network observed. For the effect of active rotation, the force chain structures disappear.

\[
k^t = 1.0 \times 10^4 \text{ N/m, } \gamma^n = 1.0 \times 10^1 \text{ 1/s, } \gamma^t = 1.0 \times 10^1 \text{ 1/s, } \mu = 0.4, \eta_1 = 15 \text{ N-m, } \eta_2 = 20 \text{ N-m/s, } r_p = 0.25 \text{ m, and } \sigma = 1 \text{ N-m s}^{1/2}.
\]

We integrated the equation with the Euler-Maruyama scheme using \(\Delta t = 0.001 \text{ s}\). Initially, pedestrians are randomly distributed in the system. The interaction terms, the size of particles are increase gradual manner from \(t = 0\) to \(10 \text{ s}\) to avoid spatial overlap. The system is settled down up to \(t = 20 \text{ s}\). Then, after these terms fully introduced, rest of terms were introduced to begin numerical simulation of Eq. (1) and (2).

\section{RESULT AND DISCUSSION}

The results of the our model is exemplified in Fig. 4. In figure 4 (a)-(c), we show the behavior when \(B = 0\). This situation is almost the same as prior study. Figure 4 (a) shows typically observed behavior of current model: lane formation, avalanche, and clogging. The phase diagram of current system with parameters: the packing ratio \(\phi\) and the population ratio \(R\) is shown in Fig. 4 (b). We measured the number of pedestrian \(N_{th}\) crossing boundary at the left and the right in \(T = 10 \text{ s}\). Here the ideal number of pedestrian crossing boundary without collision \(N_{id}\) in \(T \text{ s}\) is estimated by \(N_{id} = v_0 T N_{tot}/L_x\), where \(N_{tot}\) is total number of pedestrians. We define flow rate \(j = N_{th}/N_{tot}\), and its average and variance is defined by \(J = \langle j \rangle\) and \(V = \langle (j - J)^2 \rangle\). \(J\) and \(V\) for \(\phi = 0.7\) is plotted in Fig. 4 (c). Flow rate is defined by the number ratio of particle crossed boundary within When \(\phi\) and \(R\) is small, pedestrians flow smoothly, with high \(J\) and small \(V\) while making lane structure. At high \(\phi\) and \(R > 0.5\), average flow rate \(J\) becomes 0, and they shows clogged structure. In between these parameters, the fluctuation of flow rate \(V\), where clogging and flowing alternated stochastic manner: avalanche. These results are consistent with the prior study [13].

Active rotation due to psychological effect increase fluidity of the system as shown in Fig. 4 (d). When \(B\) is increased, even clogging situation becomes smoothly flowing lane formation phase. This result is counter intuitive, as increase of the psychological repulsion increase effective occupation area, and should enhance clogging.

We analyzed the physical stress in detail to grasp the essential mechanism of fluidization due to the effect of \(B\). We obtained minimum principal stress for each pedestrian \(\sigma_3\), which is essentially compressive stress. The averaged value of the size \(\sigma_3\) is plotted in Fig. 4(a). As seen, \(\sigma_3\) decreases with the increase in \(B\), when the system become fluidized. The snapshots as well as force chain structure obtained to visualize the effect of \(B\). The force chain is reconstructed based on the algorithm proposed by Peters et al. Here we show the typical snapshot at \(\phi = 0.8\) (Fig. 4(b, c)) where system stays as clogged even with \(B = 1000\). In Fig. 4(b), the data with \(B = 0\) is shown. Large void space is noted, with long force chain. By contrast, with \(B = 1000\), void space is now absent and pedestrians are homogeneously distributed. The force chain is now localized, and does not span whole system. It is known that the bridging of force chains between the boundary fix particles in the chains. We confirmed that the increase in \(B\) leads larger effective occupation area as expected. However, the active rotation \(B\) induces fragmentation of force chain, finally results in the decrease of average compression force \(|\sigma_3|\). We may also recognize such fluidization is due to the flow induced by the collective effect of active rotor[10].

\section{CONCLUSION}

In this study, we considered a model of pedestrians with anisotropic shape and surface friction, as well as the active rotation due to psychological effect. A pedestrian is modeled by the combination of three circles walking towards two different direction. A pedestrian experiences physical force and torque due to excluding volume effect and coulomb friction. We newly introduced active torque, modeling psychological effect to evade face-to-face situation. We confirmed that the active rotation increase the effective occupation area for each pedestrian, but it also fragments force chain structures. Overall, the system is fluidized by the effect of the active rotation.

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