STUDY ON AIRCRAFT EVACUATION MODELING AND MODEL PARAMETERS BASED ON SOCIAL FORCE

Kun Chen*, Yibing Wu*, Tianchun Zou*
***Laboratory of Civil Aircraft Airworthiness Technology, CAAC,**
Civil Aviation University of China, Tianjin 300300, China

Keywords: *Aircraft emergency evacuation; Partial evacuation experiment; Social force model; Model parameter; Cabin configuration;*

Abstract

Emergency evacuation is an important factor to ensure passengers' safety after an aircraft accident. In order to predict passengers' emergency behavior in aircraft cabin, the simulation model applicable to aircraft emergency evacuation was established. In this paper, the force balance phenomenon which means the passenger keeps still in a certain position occurred when simulating aircraft emergency evacuation because of the limitation of original social force theory. A partial emergency evacuation experiment was made to modify the psychological repulsion between passengers and physical boundary in the original social force model. The modified model was applied to simulate the emergency evacuation test conducted by the Transportation Development Center of Canada. The simulation data shows that force balance phenomenon is eliminated, and the modified social force model can effectively predict the emergency evacuation behavior of passengers in aircraft cabin.

1 General Introduction

Aircraft cabin emergency evacuation after the accident is a key factor affecting cabin safety. Under current airworthiness regulations set by FAA, to assess the new aircraft evacuation capability, for an airplane carrying more than 44 passengers, the cabin configuration with the maximum seating capacity is required to demonstrate that the passengers and crew can be evacuated from aircraft to the ground under simulated emergency conditions within 90 seconds by aircraft manufacturers [1]. Compliance with this rule is demonstrated by carrying out a full-scale evacuation demonstration, commonly known as the "90 second certification trial". The certification trial spends too much time and money, and participants are vulnerable to injury. Therefore, computer simulation has become an important method to study the characteristics of passenger emergency evacuation under the cabin configuration [2].

The social force model is a continuous microscopic simulation model of pedestrian movement where every pedestrian is treated as an individual. It can explain the pedestrian behavior driven by internal and external factors in the dynamic surroundings. Under the cabin environment, the "bottleneck" phenomenon will appear in the emergency evacuation, which can not be simulated by the cellular automata model and other models [3, 4]. The social force model can express this conflict between man and man or between man and obstruction in terms of "force", and reflect more details when the passenger walks. In this paper, we found the force balance phenomenon when simulating aircraft evacuation process based on the original social force model. Here, force balance phenomenon means that the pedestrian can not move and keep still when getting through bottlenecks. Social force model was modified to be applied to the pedestrian evacuation process under cabin configuration. Significant improvement includes the following aspect: an influential factor is added into the modified model and an appropriate range of the factor is given. By taking account into the factor, a series of computer simulations are conducted to evaluate the impact on aircraft emergency evacuation, and the result shows that the modified social force model have a good performance on predicting the emergency evacuation behavior of passengers in aircraft cabin.

2 Analysis of social force model for aircraft emergency evacuation

2.1 Social force model

The social force model describes a pedestrian's movement with intention to reach certain destination at a certain target time under the action of multiple forces. In this model, the change of velocity at time t can be presented by Eq. (1).

$$m_i \frac{d\mathbf{v}_i}{dt} = m_i \frac{v_i^0(t)\mathbf{e}_i^0(t) - \mathbf{v}_i(t)}{\tau_i} + \sum_{j(\neq i)} \mathbf{f}_{ij} + \sum_{W} \mathbf{f}_{iW} \quad (1)$$

Where, Each of N passengers i of mass m_i likes to move with a certain desired speed v_i^0 in a certain direction $\mathbf{e}_i^0$, and therefore tends to correspondingly adapt his or her actual velocity $\mathbf{v}_i$ with a certain characteristic time τ_i. The second term in the right hand of Eq. (1) represent the force between passengers i and j. And the last term in the right hand of Eq. (1) represent the force from the wall W.

- Self-driven force ($\mathbf{f}_i^0$). As shown in Fig. 1, the first term of Eq. (1) represents the motivation to move forward. Pedestrian will keep certain desired speed without changing their speed vectors dynamically if there are no stimuli of surrounding environment.
- Interactive force from other pedestrians ($\mathbf{f}_{ij}$). The second term of Eq. (1) represents the interactions to other passengers. It is assumed that one conflicting pedestrian within the subject pedestrian's range will generate a circle force field that results in repulsive effect to the subject pedestrian, which is called psychological force $\mathbf{F}_{si}$. Besides, when a large number of passengers gathered in the narrow space, such as the cabin, passengers will inevitably come into touch with surrounding passengers during the evacuation leading to physical forces including the normal extrusion force $\mathbf{N}_{ij}$ and the tangential friction force $\mathbf{T}_{ij}$. The force is shown in Fig. 2.
- Repulsive force from the wall ($\mathbf{f}_{iw}$). The force from the wall is similar with the interactive force from other pedestrians and the wall may refer to unmovable obstacles such as cabin partitions, seats, etc. The corresponding interaction force with the wall is given by Eq. (7) and is shown in Fig. 3.

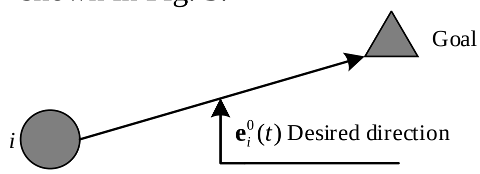


Fig. 1. Self-driven force.

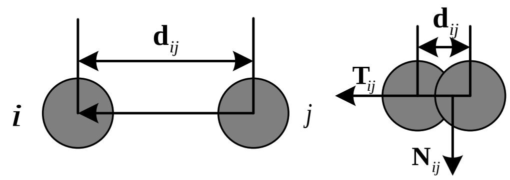


Fig. 2. Repulsive force between passenger i and j.

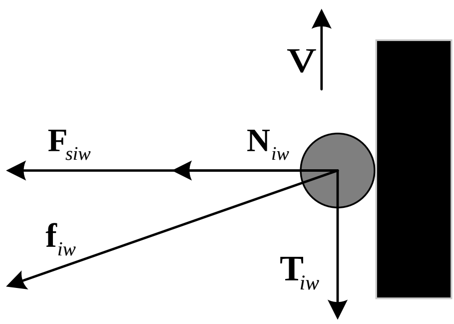


Fig. 3. Force from the wall.

$$\mathbf{f}_i^0 = m_i \frac{v_i^0(t)\mathbf{e}_i^0(t) - \mathbf{v}_i(t)}{\tau_i} \quad (2)$$

$$\mathbf{f}_{ij} = \mathbf{F}_{si} + \mathbf{N}_{ij} + \mathbf{T}_{ij} \quad (3)$$

$$\mathbf{F}_{si} = A_i \exp\left[\left(r_{ij} - d_{ij}\right) / B_i\right]\mathbf{n}_{ij} \quad (4)$$

$$\mathbf{N}_{ij} = kg\left(r_{ij} - d_{ij}\right)\mathbf{n}_{ij} \quad (5)$$

$$\mathbf{T}_{ij} = \kappa g\left(r_{ij} - d_{ij}\right)\Delta v_{ij}^{t}\mathbf{t}_{ij} \tag{6}$$

$$\mathbf{f}_{iw} = \left\{A_i \exp\left[\left(r_i - d_{iw}\right)/B_i\right] + kg\left(r_i - d_{iw}\right)\right\}\mathbf{n}_{iw} - \kappa g\left(r_i - d_{iw}\right)\left(\mathbf{v}_i \cdot \mathbf{t}_{iw}\right)\mathbf{t}_{iw} \tag{7}$$

$$\mathbf{f}_{iw} = \mathbf{F}_{swi} + \mathbf{N}_{iw} + \mathbf{T}_{iw} \tag{8}$$

In Eq. (7), A_i is the intensity of the interaction, and B_i is the range of the repulsive force. The function $g(\theta)$ is zero if the passengers do not touch each other ($\theta < 0$, and $\theta = r_i - d_{iW}$), otherwise, it is equal to the argument θ. The detailed other parameters in the formula can be found in Ref. [5, 6].

2.2 Problem of social force model simulating aircraft emergency evacuation

In the simulation, according to the real cabin configuration of 737-200, the pedestrians in Anylogic™, can have the state of evacuating [7]. When pedestrians are evacuating to the target location with emergency scenarios, the range of average speed and diameter are (0.96m/s, 1.25m/s) and (0.363m, 0.469m), respectively [8]. The key parameters of cabin are shown in Table 1, and the partial cabin configuration is represented in Fig. 4.

Table 1.The basic parameter selection of cabin.

Cabin configuration	Aisle width (m)	Bulkhead width (m)	Pitch width (m)	Exit width(m)
Parameter value	0.52	0.62	0.74	1.02

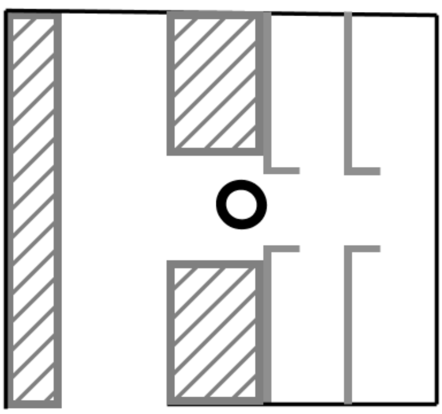


Fig. 4. Simulation scene of cabin.

The fact shows that the actual bulkhead width is enough for passengers to pass, but in the aircraft evacuation simulation they can not move through the bulkhead. It is because passengers in the aircraft cabin structure get “force balance” in a certain position, that is, the repulsive force from wall toward pedestrian *i* and his/her self-driven force achieve balance, making the passenger keeping still. Fig. 5 shows the existing force of pedestrian *i*.

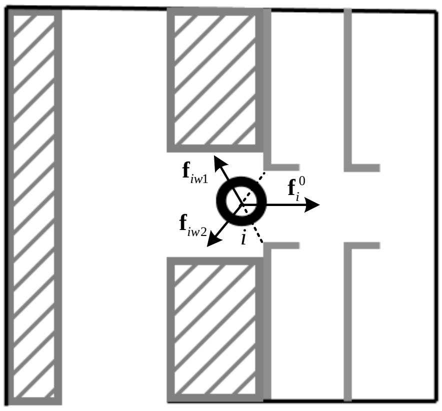


Fig. 5. The force of passenger *i*.

For social force model calibration, a hybrid method containing empirical trajectory data and simulation data of pedestrian movement in large-scale building or other scenarios has been used by Helbing[9]. However, the configuration between large-scale building and aircraft cabin is obviously different. The differences include:

- Emergency evacuation route for passengers are relatively fixed under the aircraft cabin configuration, and they have less choice, causing the passengers to be gathered together to evacuate;
- The cabin has many obstacles such as seats, lavatory, district ceiling and so on. Passengers in cabin would inevitably touch with the seats when getting through the aisle, which could not comply with the phenomenon that pedestrians keep enough distance from the wall based on the original social force model [5, 6].

3 Study on simulation model of aircraft emergency evacuation

3.1 Partial evacuation experiment

In view of the problem on the original social force model, the partial evacuation experiment was repeated twice independently to observe the passengers' characteristics in the cabin configuration and obtain the evacuation data. The partial experimental configuration is shown in Table 2 and Fig. 6.

Table 2. The basic parameter value of experiment cabin.

Cabin configuration	Aisle width (m)	Bulkhead width (m)	Pitch width (m)	Exit width(m)
Parameter value	0.53	1.01	0.80	1.07

Fig. 6. Snapshot of the experiment process.

The overall layout of the experiment cabin is similar with the actual cabin, such as the aisle width, exit width, bulkhead width and pitch width seen in Table 2. It ensures that the ease of leaving the seat is like that of actual cabin, and the cabin's narrow and sealing characteristics wouldn't be changed.

In this experiment, fifty-four 22-year-old university students consisting of 30 males and 24 females were randomly selected as participants, and the evacuation process was recorded with camera. The evacuation time for each passenger in one of the experiment is shown in Fig. 7. The first passenger evacuation time is 3.28 seconds, and the total evacuation time is 41.96 seconds, while the mean total evacuation time is 38.61 seconds for the partial evacuation experiment. The range of average speed is (1.15m/s, 1.25m/s) for males and (1.05m/s, 1.15m/s) for females, and diameter is (0.349m, 0.499m), respectively. All the information are input into the Anylogic^{TM} as the basic data, and Anylogic^{TM} simulation process are shown in Fig. 8.

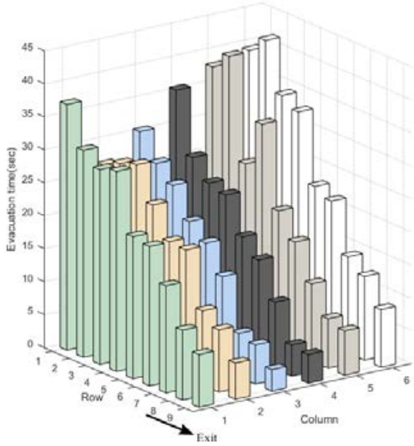


Fig. 7. Evacuation time for each passenger in one of the experiment

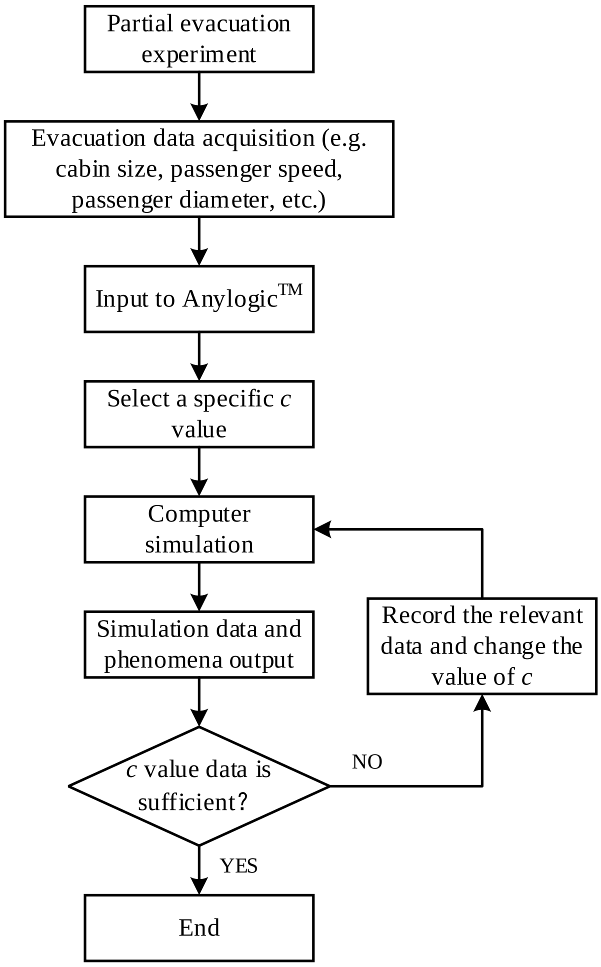


Fig. 8. Anylogic^{TM} simulation flow chart.

3.2 Modified social force model

3.2.1. Analysis of the modified social force model

In the original social force model, the pedestrian would try to keep a certain distance from the wall to prevent the collision during the walking process, and this is controlled by the "psychological repulsive force" between the pedestrians and wall. The psychological repulsive force formula is presented in Eq. (9).

$$\mathbf{F}_{swi} = A_w \exp\left[\left(r_{iw} - d_{iw}\right) / B_w\right]\mathbf{n}_{iw} \qquad (9)$$

In Eq. (8), A_w = 10 m/s^2, B_w = 0.2m, these values were got in the large-scale building [5]. While the cabin configuration has a number of obstacles, individual would not have enough distance to avoid obstacles during evacuation. It means that the range of repulsive force in cabin configuration is less than the distance required by the social force model in large-scale building.

According to the above analysis, considering the influence of relative distance on the psychological repulsive force based on the original social force model, we try to modify the social force model by reducing the psychological repulsive force between pedestrians and wall. Thus, relative distance influence coefficient *c* is introduced to solve the problem of 'balance force'. We modify the psychological repulsive force of pedestrian *i* from the wall, which can be expressed as:

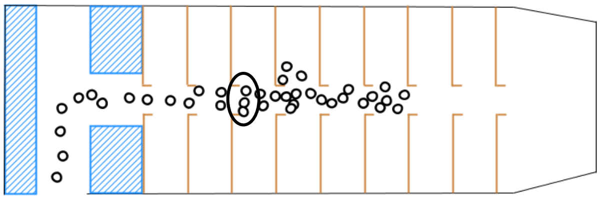
$$\mathbf{F}_{swi} = A_w \exp\left[\left(r_{iw} - d_{iw}\right) / \left(c * B_w\right)\right]\mathbf{n}_{iw} \qquad (10)$$

Where c denotes the influence between pedestrian *i* and wall.

In order to claim the effect of *c* on psychological repulsive force, the partial evacuation experiment is modeled and simulated, and simulation process is seen in Fig. 8. In this simulation, when *c* takes different values, the average, minimum and maximum distribution of total evacuation time (T_{total}) under 100 runs are shown in Table 3.

Table 3. Simulated evacuation time under parameter *c*.

	c=0.56	*c*=0.5	*c*=0.45	*c*=0.42	*c*=0.39
T_{total} /Min (s)	46.76	42.58	34.50	30.42	28.52
T_{total} /Mean (s)	47.92	45.58	38.61	35.36	32.15
T_{total} /Max (s)	49.08	47.95	43.23	38.75	34.84
STD	1.34	1.56	1.66	1.52	1.32



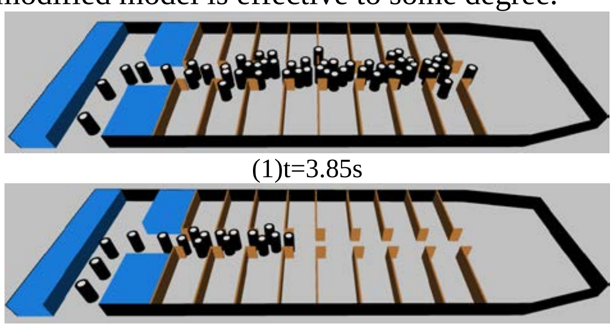
c=0.42, t=11.25s.

Fig. 9. Simulation process of passengers.

It can be seen from Table 3 that the total evacuation time decreases with the decrease of psychological repulsive force due to the reduction of *c* value. When *c* ≤ 0.5, the force balance phenomenon in the evacuation process are obviously eliminated, and the simulated evacuation time approximated to the experimental evacuation results. However, when *c* ≤ 0.45, three pedestrians are quickly pass the aisle (black circle in Fig. 9) at the same speed, which does not match the characteristic that the cabin aisle can only accommodate two persons to pass in the actual experiment. With the *c* value's reduction, the phenomenon of three people at the same time passing the main aisle is more obvious, so the smaller *c* value is not appropriate.

3.2.2. Results of the modified model

The simulation results indicate that each passenger's evacuation time from the seat to the exit is approximately equal to the real time when *c* is (0.45, 0.5). When *c* = 0.45, as showed in Fig. 10, the force balance phenomenon disappeared. Meanwhile, some phenomena arose in the simulation process (e.g., "arch effect" and avoiding collision) were in line with those in classical articles [8], which proved that the modified model is effective to some degree.



(1)t=3.85s

(1)t=25.92s

Fig. 10. Simulation process of passengers.

After performing 100 simulations, the distribution of evacuation time is showed in Fig.

11 and Table 4, and the mean first evacuation time T_{first} is 5.02 seconds, while the mean total evacuation time T_{total} is 38.61 seconds. The mean evacuation time is (37.5s, 40.5s), and it is in good agreement with the experimental results. In Fig. 12, the simulation evacuation time curve agrees with that of the two experiments. The first eighteen passengers' simulation evacuation time was slightly bigger than the experiment data. It is because that there is no one in front of the evacuees when the evacuation begins, as a result the passenger speed in the real trials is bigger than in simulation.

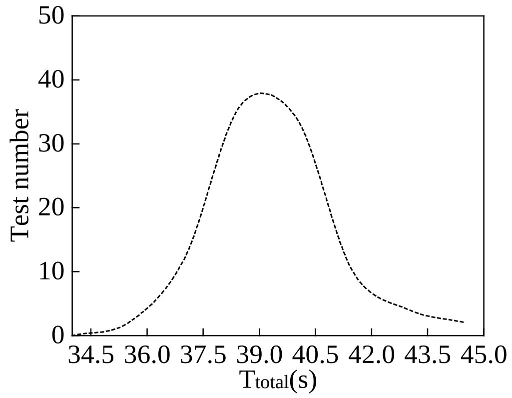


Fig. 11. Evacuation time distribution (100 simulations).

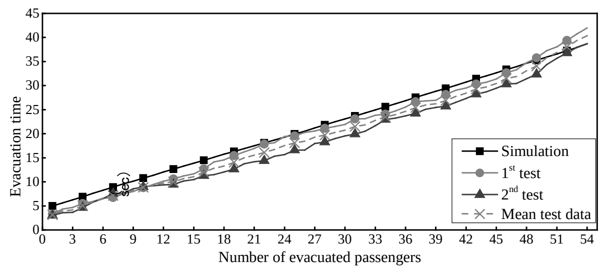


Fig. 12. Comparison between the evacuation experiments and the simulation.

Table 4. Simulated evacuation time.

	T_{first} (s)	T_{total} (s)
T_{total} /Min	4.23	34.50
T_{total} /Mean	5.02	38.61
T_{total} /Max	5.64	43.23
STD	0.29	1.66

4. Quantitative verification

4.1. Simulation environment and parameter settings

In this study, according to the evacuation trials carried out by the Canadian Department of Transportation, all settings in our simulation based on the modified social force model, are the same as the trials documented [10]. Fig. 13 is the straight aisle cabin configuration. Passengers in the cabin are different individuals influenced by gender, body size and other factors. The passengers were partitioned into two parts: the men proportion is 64%, whose expected speed is (1.05m/s, 1.35m/s); the proportion of women is 36%, and the average range of expected speed inside the cabin is (0.98 m/s, 1.26 m/s) [11]. The other parameters set in the simulation model are shown in Table 5.

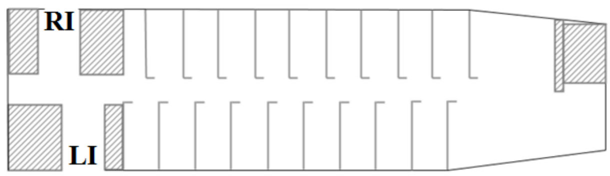


Fig. 13. Cabin configuration of the experiment.

Table 5. The initial settings for the simulation

Attributes	settings	
Total number of passenger	51	
Diameter (m)	(0.363，0.469)	
Sex distribution	Men: 33 (64%)	Women: 18 (36%)
Exit choice	L1: 26 (51%)	R1: 25 (49%)
Speed distribution in cabin [11] ($m\cdot s^{-1}$)	Men: (1.05，1.35)	Women: (0.98，1.26)
Pre-evacuation time (s)	0.00	0.00

4.2. Simulation results analysis

In our simulation scene, as seen from Fig. 14 and Fig. 15, the results of evacuation time obtained from the two exits agree with those of the trials in the straight aisle for competitive scene conducted by the Canadian Department of Transportation. However, the evacuation time obtained from RI exit was slightly smaller than the data from trials. The real reason is that the LI is slightly bigger than RI in cabin simulator in the real trials, which may lead that passengers need to reduce their moving speed to evacuate safely through RI exit. Results based on modified social force model are similar to the simulation data based on VacateAir model and the actual test [12], as shown in Fig. 16. The phenomena of avoiding collision appeared in the evacuation process, which indicates that the simulation model can accurately reflect the actual evacuation process, as shown in Fig. 17. The modified social force model in this paper is effective in simulating the aircraft emergency evacuation.

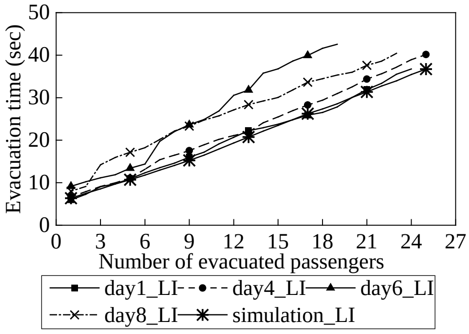


Fig. 14. Evacuation time of light, straight aisle, competitive scenario
(exit through R1, based on 100 simulations).

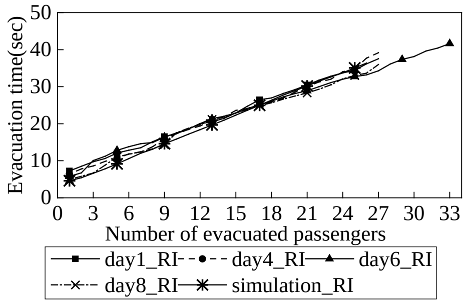
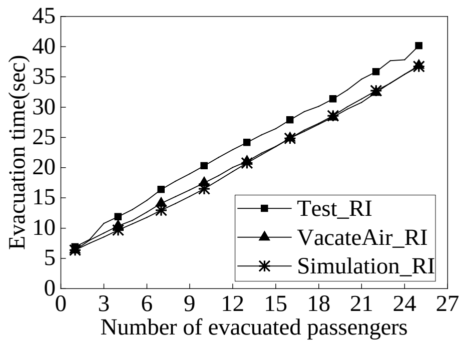
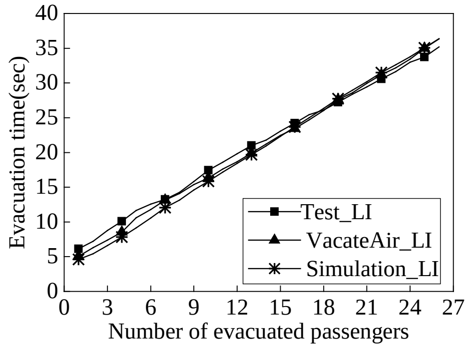


Fig. 15. Evacuation time of light, straight aisle, competitive scenario
(exit through L1, based on 100 simulations).

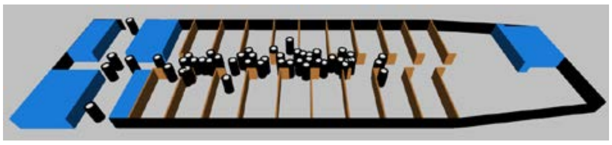


(1) Evacuation time (exit through R1, based on 100 simulations).

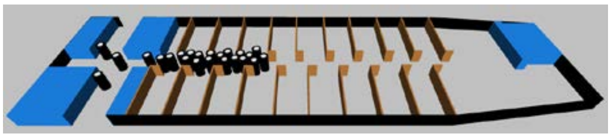


(2) Evacuation time (exit through L1, based on 100 simulations).

Fig. 16. Comparison of the simulation results of the model and VacateAir.



(1) t=6.36s.



(2) t=21.82s.

Fig. 17. Simulation state at the different time.

5. Conclusions

This study makes two main contributions. Firstly, we find out force balance phenomenon when simulating aircraft emergency evacuation based on the original social force model. Secondly, we further develop the social force model and more simulations are conducted. The results show that the introduction of the relative distance influence coefficient c can effectively reduce the psychological repulsion force in the cabin configuration. And when the value of c is (0.45, 0.5), each passenger's evacuation time from his/her seat to the exit is in good agreement with the results in the experiment, which can truly reflect the actual movement characteristics of personnel in the aircraft cabin configuration. Therefore, the simulation model of aircraft emergency evacuation established in this study is reasonable and effective.

References

[1] Code of Federal Regulations. *Aeronautics and Space. Part 25 Airworthiness Standards: Transport Category Aeroplanes*, Office of the General Register, Washington, DC, USA, 2008.

[2] Martínezval R. Computer model for numerical simulation of emergency evacuation of transport aeroplanes, *Aeronautical Journal*, Vol. 114, No. 1162, pp 737-746, 2010.

[3] You L, Hu J, Gu M, et al. The simulation and analysis of small group effect in crowd evacuation. *Physics Letters A*, Vol. 380, No, 41, pp 3340-3348, 2016.

[4] Cao S, Song W, Lv W. Modeling pedestrian evacuation with guiders based on a multi-grid model. *Physics Letters A*, Vol. 380, No. 4, pp 540-547, 2016.

[5] Helbing D, Molnár P. Social force model for pedestrian dynamics. *Physical Review E Statistical Physics Plasmas Fluids & Related Interdisciplinary Topics*, Vol. 51, No. 5, pp 4282-4286, 1995.

[6] Helbing D, Farkas I, Vicsek T. Simulating dynamical features of escape panic. *Nature*, Vol. 407, No. 6803, pp 487-490, 2000.

[7] X. Song, Z. Zhang, G. Peng, G. Shi, Effect of authority figures for pedestrian evacuation at metro stations, Phys. A, Stat. Mech. Appl. 465 (2017) 599-612. Song X, Zhang Z, Peng G, et al. Effect of authority figures for pedestrian evacuation at metro stations. *Physica A Statistical Mechanics & Its Applications*, Vol. 465, pp 599-612, 2016.

[8] Zhang Q, Qi H, Zhao G, et al. Performance Simulation of Evacuation Procedures in Post-Crash Aircraft Fires. *Journal of Aircraft*, Vol. 51, No. 3, pp 945-955, 2014.

[9] Helbing D, Shukla P K. Specification of the Social Force Pedestrian Model by Evolutionary Adjustment to Video Tracking Data. *Advances in Complex Systems*, Vol. 10, No. 02, pp 271-288, 2007.

[10] Muir H, Cobbett A. Aircraft evacuation tests-an initial assessment of the influence of various aisle configurations and lighting conditions under different evacuation scenarios. *Canada, Transportation Development Centre*, 1996.

[11] Hedo J M, Martinezval R. Assessment of Narrow-Body Transport Airplane Evacuation by Numerical Simulation. *Journal of Aircraft*, Vol. 48, No. 5, pp 1785-1794, 2011.

[12] Xue Z, Bloebaum, C. A particle swarm optimization-based aircraft evacuation simulation model – VacateAir. *Proceedings of 46th AIAA Aerospace Sciences Meeting*, Reno, Nevada, USA, January 2008.

Contact Author Email Address

Correspondence author: Yibing Wu
E-mail address: wybcauc@126.com

Copyright Statement