Study of Boeing 777 evacuation using a finer-grid civil aircraft evacuation model

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Abstract

Study on civil aircraft emergency evacuation process by using of computer model is an effective way to validate and improve the evacuation performance of aircraft. In this paper, based on the characteristics of the aircraft structure and personnel evacuation, a finer-grid civil aircraft evacuation model (FGCAEM) is built. In this model, the effect of seat area, others and fire products on escape process is considered. Simulations reproduce typical characteristics of aircraft evacuation, such as the movement synchronization between adjacent pedestrians, route choice and so on. It is indicated that evacuation efficiency will be reduced significantly in case of fire, especially in the last period of the evacuation process. Results will be helpful for the design of security auxiliary equipment of airplane and promoting management procedure to emergency case.

Keywords: civil aircraft; finer-grid; evacuation; Boeing 777

1. Introduction

According to the Federal Aviation Regulations (FAR (2002)), “for airplane having a seating capacity of more than 44 passengers, it must be shown that the maximum seating capacity can be evacuated from the airplane to the ground under simulated emergency conditions within 90s.” Furthermore, an actual demonstration using the test criteria, i.e. “90s certification test”, is needed generally in the airworthiness certification.
However, there are several difficulties with the “90s certification test” (Galea (2006)). First, there is considerable threat of injury to text participants. Published statistics for the periods 1972 and 1991 reveal that a total of 378 volunteers (or 6% of participants) sustained injuries ranging from cuts and bruises to broken bones. Second, a real emergency scenario is so difficult to reach that there may be a discrepancy between test and actual evacuation. For example, in the Manchester disaster of 1985, the last passenger escaping from the burning B737 aircraft cost 5.5min, but in a certification test 15 years earlier, the entire load of passengers and crew finished evacuation in 75s. Third, each full-scale evacuation demonstration test will be extremely expensive and time-consuming.

Consequently, along with the development of computer simulation technology, researchers began to simulate the evacuation process of civil aircraft under emergency. On the one hand, the simulation would be a useful supplement for actual demonstration test (Galea (2006)), on the other hand, simulated results can be used to assist the aircraft safety evacuation design and as a basis for optimization of aircrew emergency disposal procedures (Xue and Bloebaum (2008)).

Evacuation simulation technology is widely used in the field of construction in firstly, that kinds of model were built, including social force model (Helbing et al. (2000)), lattice gas model (Tajima and Nagatani (2001)), cellular automata model (Burstedde et al. (2001)), multi-grid model (Song et al. (2006)) and agent-based model (Tang and Ren (2008)), etc. Simulation reproduced the complex behavior phenomenon during egressing in typical structure, e.g. “herding” in the structure with multi-exits (Low (2000)), “wider is narrower” in the passageway and “faster is slower effect” in crowds (Song et al. (2006)).

Nevertheless, because of the particularity of the space, structure and facilities, the emergency evacuation process in aircraft is obviously different from building. Therefore, the evacuation model for building cannot be directly applied to the evacuation simulation of civil aircraft. Recently, researchers had built several special evacuation models for aircraft, such as STRATVAC (Cagliostro (1984)), airEXODUS (Galea et al. (1998)), and VacateAir (Xue and Bloebaum (2008)), etc. Using these model, the effect of environmental condition (such as exit setting (Blake et al. (2002)), and crews’ guidance (Galea et al. (2004))), passengers’ physiological characteristics (such as gender, age and size (Wang et al. (2012))) and psychological characteristics (such as panic (Miyoshi et al. (2012)) and hesitation (Amos and Wood (2005))) on the evacuation process of aircraft was studied.

In the existing aircraft evacuation models, the size of the grid is matched with pedestrian size. As a result, the pedestrians queue in order and the size of exits, obstacles and aisle has to equal to integral multiples of the pedestrian size. However, in reality, pedestrians move in dislocation, and the size of exits, obstacles and aisle are irregular and not integral multiples of pedestrian size. For these reasons, we build a Finer-Grid Civil Aircraft Evacuation Model (FGCAEM), in which the space is discretized into grids with the size of 0.1m×0.1m, smaller than the traditional size of 0.4m×0.4m. Using this model, we carried out aircraft evacuation simulation and focused on the effect of seats, interaction between evacuees and fire case on the evacuation process.

2. Modelling

This paper takes Boeing 777-200 as simulation subject (Fig. 1a). There are total 323 seats, and 8 exits are symbolized by \( E_n(n = 0,1,...7) \) (Fig. 1b).

2.1. Space meshing

The space shown in Fig.1a is first discretized into grids with the size of 0.1m×0.1m, and the grids are divided into four categories: normal passable grids, seat grids, obstacle grids and exit grids, correspond to what they represent. The normal passable grids represent area that passengers can easily pass through, such as aisle between columns of seats and open ground in front of exits. The seat grids indicate the personal space passengers have when sitting, which are also passable for passengers but by sideways. The obstacles grids include normal obstacles and seat back. Each exit occupies 8 grids sites in width, and each pedestrian occupies 4×4 grid sites.
2.2. Drift direction determining

In this paper, the drift direction denotes the direction that pedestrians prefer moving to with a higher probability. It is recognized that in evacuation process pedestrians prefer to select the nearest exit and then move in the direction leading to the selected exit. According to the static floor field presented by Burstedde et al. (2001), the two-dimensional array \( S_n \) \( (n = 0, 1, ..., 7) \) is used here to record the shortest distance (the least number of grids) from each grid point to \( E_n \), which is calculated using a repetitive function:

\[
S_n[i \pm 1][j \pm 1] = S_n[i][j] + S_{add}
\]  

(1)

Where \( S_n[i][j] \) represents the potential distance from grid \((i, j)\) to the exit \( E_n \), \( S_n[i \pm 1][j \pm 1] \) is for each neighbouring grid in forward, backward, left and right of grid \((i, j)\). Obviously, if \( S_{add} \) is 1 or other constant, the action of \( S_n \) is just same as in Floor Field Model (Burstedde et al. (2001)). We adopt different values of \( S_{add} \) to treat seat grids differently from normal passable grids, which will be detailed in the following sections.

Each pedestrian has 4 neighbouring grids in forward, backward, left or right direction, see Fig. 2. The drift direction of a pedestrian is determined by the expression (2), where \( S_k^* \) represents the minimum distance from the \( k \)th grid, in the 4 grids of one neighbouring direction of the pedestrian, to \( E_n \).
\[
\min\left\{ \sum_{k=1}^{4} \min_{l=0,1,...,7}\left\{ S_{l}^{k} \right\}_{\text{forward, backward, left, right}} \right\}
\]

Fig. 2. A pedestrian and his neighboring grids. The circle indicates a pedestrian. The numbered grid is the neighboring grid.

2.3. Transition rule

Each pedestrian moves to the drift direction without backwards. Considering that a pedestrian occupies multiple grids and there is indoor obstacle in this study, we adopt a modified rule based on the transition rule of traditional lattice gas (LG) model (Tajima and Nagatani (2001)).

2.4. Specific rule

Compared with the evacuation in buildings, evacuation in airplanes is specific for its small space and complex inner structures, which performs mainly on the following aspects: (1) Outstripping others is difficult in narrow passage, thus passengers egress in order of distance to exits; (2) It is demonstrated that in the scenario with multi-row seats, pedestrians will avoid to pass through seat area if the space between two adjacent rows is small (Chen et al. (2013)). Similarly, for wide body aircraft with two aisles, the probability of passengers passing through seat area between the two aisles is smaller. (3) Slides are necessary in evacuation process because of the height difference between exits and ground. Specially, “Hesitation” would emerge in the process of passengers leaving exits to slides (Jungermann and Göhlert (2000)). (4) Affected by familiarity, queuing length, and guidance from crews and so on, passengers would show “preference” when choosing exits.

In response to those phenomena or laws, some specific rules are given in this model:

Update procedure based on position

The update procedures used in evacuation simulations mainly have 3 types—parallel update, shuffled sequential update and ordered sequential update. However, based on the experimental observation, it is found that in the building with dense crowd and complex multi-obstacle pedestrians usually consider the moving tendency of the front pedestrians. So that an update procedure based on position is presented by Zhang et al. (2008), in which the pedestrians are updated in turn according to the distance from their current position to the exits.

The update procedure based on position is used in this model, and its suitability would be discussed by comparing simulation results between update procedure based on position with other update procedures.

Determination of the $S_{\text{add}}$

The parameters $\omega_{\text{seat}}$ and $\omega_{\text{others}}$ are used to present the effect of seats and others on route choice, then the $S_{\text{add}}$ in equation (1) is defined as follows:
The value of $\omega_{\text{seat}}$ is given in equation (4), which determines the difficulty of passing through seat area, i.e., the larger $\omega_{\text{seat}}$ is, the more difficult passing through seat area becomes. Similarly, the $\omega_{\text{others}}$ is given in equation (5), and it determines the pedestrians’ wish to avoid congestion sections. The $\omega_{\text{fire}}$ represents the degree of influence of fire, which is presented in our previous work (Fang et al. (2012)). $C$ and $T$ represent the value of extinction coefficient and temperature of corresponding grid in case of fire.

\[
\omega_{\text{seat}} = \begin{cases} 
0; & (i \pm 1, j \pm 1) \text{ are normal passable grids} \\
\geq 0; & (i \pm 1, j \pm 1) \text{ are seat grids}
\end{cases} \quad (4)
\]

\[
\omega_{\text{others}} = \begin{cases} 
0; & (i \pm 1, j \pm 1) \text{ are unoccupied grids} \\
\geq 0; & (i \pm 1, j \pm 1) \text{ are occupied by others}
\end{cases} \quad (5)
\]

**Hesitation time**

The $t_{\text{delay}}$ is used here to represent the hesitation time during the process of passengers leaving exits to slides. We assume that when reaching exits pedestrians will leave not immediately but in $t_{\text{delay}}$ seconds.

**Preference for exits**

To model the “preference” when choosing exits, the $\rho_n (0 < \rho_n \leq 1)$ is introduced and then the expression (2) for determining drift direction is replaced by a new equation (6), which means that the smaller $\rho_n$ is, the larger the probability of choosing $E_n$ is.

\[
\min \left\{ \left. \sum_{k=1}^{4} \min \{ \rho_n \cdot S_n^k \} \right| \text{forward, backward, left, right} \right\} \quad (6)
\]

**3. Simulation and results**

In the model, time step is 0.1s and pedestrians’ desired speed is 1.0m/s. Number of pedestrians is 323, corresponding to the number of passenger seats, and all pedestrians are placed in their seats before starting simulation. For simplicity, the effect of baggage on evacuation and differences in human's nature attributes are not considered.

According to aircraft accident statistics (Galea et al. (2004)), exit or slide malfunctions frequently occur, furthermore, no more than 50% of the exits is used in the industry standard 90s evacuation certification trial. Thus, 5 different exit settings with half of the exits available are used in the simulation (Fig.3).

For the aircraft evacuation, the exit preparation time should be considered. Referencing previous study (Galea et al. (2003)), we set the exit preparation time at 14s for every case considered within this study. That is, the exits are prepared at 14s and the passengers begin to evacuate through the exits.

Considering the randomness of simulation process, the results of evacuation time and proportion of pedestrian choosing each exit are an average got by simulating each case 100 times. In contrast, the results of pedestrians out against time and evacuation trajectory are given by one simulation.

**3.1. Without fire**

In our previous study, the suitability for aircraft evacuation of update procedure and the effect of hesitation and preference on evacuation process had been discussed. The conclusion is that update procedure based on position
conforms to evacuation movement characteristic of aircraft; hesitation caused by fair when passengers travelling from exits to slides will reduce evacuation efficiency significantly; adjusting proportion of pedestrians choosing each exit will affect obviously the evacuation time.

![Exit setting](image)

Fig. 3. Exit setting. Symbols in each setting represent whether the exits in the corresponding point are available. ○ represents the corresponding exit is available. × represents the corresponding exit is unavailable.

![Evacuation trajectory](image)

Fig. 4. Evacuation trajectory. (a) \( \omega_{\text{seat}} = 0, \omega_{\text{others}} = 0, \omega_{\text{fire}} = 0 \); (b) \( \omega_{\text{seat}} = 4, \omega_{\text{others}} = 0, \omega_{\text{fire}} = 0 \); (c) \( \omega_{\text{seat}} = 4, \omega_{\text{others}} = 1, \omega_{\text{fire}} = 0 \)

![Evacuation results](image)

Fig. 5. Evacuation results with different set of \( \omega_{\text{seat}} \) and \( \omega_{\text{others}} \). (a) proportion of pedestrian choosing each exit and evacuation time; (b) pedestrian out against time.
In this paper, the function of $\omega_{\text{seat}}$ and $\omega_{\text{others}}$ are further investigated. For exit setting (a) with $t_{\text{delay}} = 0$ and $\rho_n = 1$, simulations are carried out by adopting different value of $\omega_{\text{seat}}$ and $\omega_{\text{others}}$. As shown in Fig. 4a, the seat grids in the model will be same as the normal passable grids if $\omega_{\text{seat}} = 0$, so that pedestrians on the seats of the bottom column usually cross the middle column, and then queue in the above aisle to egress. Thus, the bottom aisle is rarely used in the evacuation and result in lower evacuation efficiency (Fig. 5), which does not match reality. When $\omega_{\text{seat}} = 4$ (Fig.4b and 4c), with the increase of the difficulty of passing through seat area, most of pedestrians on the...
seats of bottom side will first enter the bottom aisle and then queue to egress. However, there are also little difference in the trajectory between $\omega_{\text{others}} = 0$ and $\omega_{\text{others}} = 1$, as shown in the tagged image regions by dash circles in Fig.4a and Fig.4c. When $\omega_{\text{others}} = 0$, pedestrian will move in the nearest direction but not care how many people queue in this direction, which leads to longer evacuation time (Fig.5a) and lower evacuation efficiency. When $\omega_{\text{others}} = 1$, if there are multiple available escape routes pedestrian will balance the length of each route and the number of pedestrian queuing in each route, so that the trajectory result of $\omega_{\text{seat}} = 4$ and $\omega_{\text{others}} = 1$ seems more realistic.

3.2. In case of fire

To detect the effect of fire on aircraft evacuation, three different fire scenarios, named F1-F3 are assumed and simulated by using the FDS model. As shown in Fig.1b in scenario F1, the fire occurs in the red zone with number 1, and similarly in scenario F2 and F3, the fire occur in the red zone with number 2 and 3 respectively. In each scenario, the Heat Release Rate (HRR) is unified set to 850KW, and the data of temperature and visibility of fire simulation are output for the following evacuation simulation.

For each exit setting, one fire scenario is considered, that is (a)+F1, (b)+F2, (c)+F3, (d)+F1, (e)+F2 respectively. Take (a)+F1 for example, it represents the evacuation process with exit setting (a) in case of the fire scenario F1.

For all the 5 exit settings (Fig.3), it had been demonstrated by the simulation results that the exit setting (a), usually adopted in the “90s certification test”, is not the most disadvantageous condition for evacuation (see Fig. 5). The evacuation simulations in case of fire and their comparison with those in the normal condition are further carried out here. Fig.6a shows that the evacuation time of each exit setting in case of fire is more than the condition without fire. The reason is that the trend of avoiding fire, high temperature and low visibility will affect pedestrians’ choice on the evacuation path and exit. So that there are also obvious difference in the proportion of pedestrian choosing each exit between fire and no fire case, especially for exit setting (a), (b) and (e). The results of pedestrian out against time also show that the difference in the escape efficiency mainly occurs in the last part of the evacuation process.

4. Summary

This paper presented a Finer-Grid Civil Aircraft Evacuation Model (FGCAEM), in which the spatial dimensions is discretized into cells with size of $0.1\text{m} \times 0.1\text{m}$ and each pedestrian occupies $4 \times 4$ cells. In this model, airplane seats were represented by two types of cells: occupied cell for backrest and empty cell for seat cushion. Furthermore, the seat cushion cells and occupied cells by pedestrians were assigned a different property than other passable empty cells, to make them harder for pedestrians to walk through. The model also took into account the effect of fire products on pedestrians’ choice of evacuation route and efficiency.

Using the FGCAEM, this paper simulated the evacuation process of Boeing 777. Because of the finer grids, the internal structure of the airplane, and some typical characteristics during evacuation process, such as the movement synchronization between adjacent pedestrians, the choice of route and so on, were reproduced well. It was demonstrated that update procedure based on position conforms to evacuation movement characteristic of aircraft; hesitation caused by fair when passengers travelling from exits to slides will reduce evacuation efficiency significantly; adjusting proportion of pedestrians choosing each exit will affect obviously the evacuation time. The model built here could be used to validate and improve the evacuation performance of aircraft. Generally, “90s certification test” and simulation for airplane evacuation were carried out without concern on the effect of fire. However, further simulations using FGCAEM in case of fire indicated that the choice of escape route will be affected and evacuation efficiency will be reduced significantly by the fire products, especially in the last part of the evacuation process. The simulation results also suggested that the practical demonstration test should be conducted in the worst scenario that all active exits concentrated in one end of the cabin.
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