Evolution of large-scale flow structures and traces of marked fluid particles within a single-aisle cabin mock-up

Changwei Yang^{1,2}, Jiawei Liu¹, Feng He¹ (✉)

1. School of Aerospace Engineering, Tsinghua University, Beijing 100084, China

2. China Helicopter Research and Development, Jingdezhen 333000, China

Abstract

Over the past several decades, rapidly growing popularity of airline transportation has pushed many passengers and crew to focus on potential risk of contaminant transmission during commercial air travel. Understanding airflow dynamics and transport property within an aircraft cabin is critical to creating a healthy cabin environment and improving control of epidemics. This work reveals the temporal and spatial evolution process of large-scale flow structures around the aisle region and evaluates impact of airflow's large-scale flow structures (swing motion around the aisle region and large-scale vortices) on transport property by calculating traces of marked fluid particles (MFPs) passing through passengers' exhalation area within a Boeing 737-200 cabin mock-up. The Peixoto theorem has been used to interpret temporal and spatial evolution process of large-scale flow structures around the aisle region. Transport property within this single-aisle aircraft cabin is a mixed effect of the airflow's swing motion, large-scale vortices and longitudinal airflow. Airflow's swing motion around the aisle region tends to carry MFPs nearby across the aisle region and invade the large-scale vortex in the opposite side. The large-scale vortices try to control MFPs in its each separated zone. The airflow's swing motion and large-scale vortices dominate MFPs' latitudinal transmission, while longitudinal airflow dominates MFPs' longitudinal transmission.

Keywords

large-scale unsteadiness, spatial instability, contaminant transmission, LES, cabin

Article History

Received: 15 November 2016

Revised: 17 January 2017

Accepted: 17 January 2017

© Tsinghua University Press and Springer-Verlag Berlin Heidelberg 2017

1 Introduction

Due to air transportation's popularity, more and more people are travelling by air throughout the world. Air quality, especially air safety in aircraft cabin environment has become the focus of many passengers and crew (Spengler and Wilson 2003; Mangili and Gendreau 2005). Typically, aircraft cabin is a confined and ventilated environment. In general, the air circulation pattern inside a single-aisle aircraft cabin is such that air enters aircraft cabin through two horizontally opposed inlets near the ceiling, circulates across the aircraft and exits cabin through opposed outlets near the floor (Mangili and Gendreau 2005; Cao et al. 2014; Yang et al. 2016). This air circulation pattern attempts to separate airflow into separate zones and limit longitudinal airflow within aircraft cabin, to confine spread of infectious airborne diseases. Unfortunately, some undesirable cases of disease transmission have been reported in practice. For example, when severe

acute respiratory syndrome (SARS) broke out in 2003, many passengers who were seated seven rows in front, five rows behind and at opposite side region of the symptomatic passenger in a Boeing 737-300 cabin were affected. Among those interviewed passengers, as many as 18 passengers met the WHO definition of probable cases of SARS, and 4 other passengers met the cases of SARS (Olsen et al. 2003). The global SARS outbreak showed that commercial air travel played an important role in rapid spread of newly emerging or re-emerging infectious diseases both at home and abroad. Hence, it is necessary to improve our understanding of how diseases spread within aircraft cabins.

Common sources of diseases are droplets or micro-particles (residua of evaporated droplets) released into the air by sick passengers through sneezing, coughing and breathing (Bourouiba et al. 2014). These droplets or particles containing various microorganisms spread in different ranges within aircraft cabin. Heavy droplets settle directly

near disease sources for a short period of time, while light droplets are transported to other passengers far away or stay suspended within aircraft cabin for indefinite periods. Disease transmission and spread of various contaminants within aircraft cabins negatively impact health of passengers and crew. Coughing, sneezing, or movements of flight attendant and beverage cart (Trupka et al. 2011), especially ventilated airflow pattern (Yan et al. 2009), inevitably have great influence on such complicated dispersion processes of infectious viruses or contaminants. Hocking (1998) proposed that due to limited longitudinal airflow in aircraft cabin, exposure risks were usually low unless travel time was longer than 8 h and the distance was within 2 rows around a sick passenger. Yan et al. (2009) found that the “two neighboring rows” transport rule was controversial as some microorganisms rely on injection and space encroachment during the release process, while others follow airflow. The SARS outbreak incident (Olsen et al. 2003) mentioned earlier, showed that affected passengers were seated as far as seven rows from the source passenger, which indicated that SARS virus may follow airflow and travel far beyond two neighboring rows within aircraft cabins. Mazumdar et al. (2011) discovered that crew member or passenger movement could carry contaminants in its wake to many rows, and proposed this as the reason for SARS infection of passengers seated seven rows away. Zhang et al. (2009) conducted experimental and numerical investigation of airflow and contaminant transport in an aircraft cabin mockup. Li et al. (2014) conducted an experimental study of how gaseous and particulate contaminants were distributed within an aircraft cabin. Okubo (1970), Provenzale (1999) and Isern-Fontanet et al. (2004) revealed the relationship between different transport properties of coherent airflow vortices. Li et al. (2016a) introduced airflow vortex structure to analyze how airflow patterns affect contaminant transmission in an aircraft cabin. These studies on airflow and disease or contaminant transmission in aircraft cabins are meaningful, but they mainly focused on the mean air distribution, and its impact on diseases or contaminant transmission.

At the same time, many investigations also pointed out that velocity field within aircraft cabin was obviously unsteady and even unstable. For example, Garner et al. (2003) showed that velocity field varied with time, and there was about 3 to 4 minutes periodic unsteadiness in an empty Boeing 747 aircraft cabin. Baker et al. (2006) found that airflow in an unoccupied cabin was obviously unsteady, although the boundary condition was steady. Liu et al. (2012) pointed out that measurements should be taken for at least 4 minutes to obtain accurate averaged velocity and turbulence information within aircraft cabin due to airflow instability.

Zhang et al. (2013) revealed that unstable airflow was ubiquitous within airplane and required advanced testing instruments for better characterization. Cao et al. (Cao 2014) found that the entire instantaneous velocity field was dominated by unstable vortices in a B737-200 cabin mock-up. These descriptions on unsteady or unstable velocity fields appear only as a few isolated words and phrases in their papers, but indicate that unsteadiness or instability of velocity fields have been observed widely in their experimental measurements and numerical calculations. Furthermore, few researchers described the highly unsteady or unstable airflow within aircraft cabin in more detail. Lin et al. (2006) and Ebrahimi et al. (2013) presented the unsteady characteristics of airflow quantitatively, by comparing the temporal variation of air velocity obtained by large eddy simulation (LES) and particle image velocimetry (PIV) measurement. Lin et al. (2005) also described airflow’s asymmetrical flow patterns and swing motion across symmetrical plane in a double-aisle Boeing 767 aircraft cabin, by experimental measurement and transient Reynolds-averaged Navier–Stokes (RANS) simulation. Yang et al. (2016) further obtained more instantaneous airflow’s details by LES and PIV in a Boeing 737-200 cabin mock-up. More importantly, Yang et al. (2016) introduced the Peixoto theorem (Peixoto 1962) to explain the mechanism of temporal instability of velocity field. However, the impact of instantaneous unstable velocity field on diseases or contaminant transmission has not been investigated.

In this work, the detailed temporal and spatial large-scale characteristics of velocity field within a simplified full-scale fully-occupied B737-200 cabin mock-up have been revealed. The particle-paths and streak-lines of marked fluid particles (MFPs) within this unstable velocity field have been investigated. The remaining outline of this paper is organized as follows: In Section 2.1, experimental and numerical methods are briefly presented and detailed information on LES and PIV measurement can be found in (Cao et al. 2014) and (Yang et al. 2016). Methods for calculating streamlines, particle-paths and streak-lines of MFPs are introduced in Section 2.2. Section 3 is the result and discussion. Mean airflow patterns and temporal and spatial large-scale characteristics of velocity fields are presented in Section 3.1, followed by the statement of dynamic characteristics and topological structures of instantaneous velocity field in Section 3.2. This section also covers analysis of airflow’s temporal and spatial instability with the Peixoto theorem. In Section 3.3, distribution of MFPs and their trajectories for a period of 40 s are showed. Transport properties and impact of unstable velocity field are analyzed in this section. Section 4 gives this study’s conclusion.

2 Methods

2.1 Experimental and numerical methods

Figure 1(a) shows the picture of simplified, full-scale, fully-occupied B737-200 mock-up with dimensions 5.8 m (length) $\times$ 3.25 m (width) $\times$ 2.15 m (height). The cabin mock-up includes inlets, outlets, passenger seats and heated manikins. Seven rows with 42 real aircraft passenger seats and 40 heated manikins are placed in the cabin mock-up. The unoccupied two-passenger space is used to place experimental equipment. The height, surface area and sensible heat load of each seated manikin are 1.4 m, 1.339 m² and 75 W, respectively. Air supply is set to (20 ± 0.5) °C and air supply rate is (1420 ± 60) m³/h corresponding to 9.4 L/s per person. PIV technique is used for experimental measurement, and instantaneous velocity field is acquired. More details about experimental measurement can be found in (Cao et al. 2014). Figures 1(b) and (c) show the cabin model. The fourth row is used for LES. Periodic boundary condition is adopted along the longitudinal direction (corresponding to Z coordinate direction) to represent a cabin with infinite rows of seats. The LES-WALE model (Nicoud and Ducros 1999) is selected for LES, to simulate velocity field in this cabin mock-up after evaluating many models. Computed results and more details about numerical simulation, such as numerical model, grid strategy, evaluation of turbulence models involved, and computational resources can be found in (Yang et al. 2016).

2.2 Methods for calculating streamlines, particle-paths and streak-lines

Streamlines are curves which are tangent to the velocity vector of flow everywhere at the desired time, t_0 . By integrating differential equation at a pseudo-time, τ , streamlines show the travelling direction of fluid elements at any point in the

flow. Streamlines can be computed by integrating ordinary differential equations as follows:

$$\frac{d}{d\tau} \vec{x}(\tau) = \vec{v}(\vec{x}(\tau), t_0)$$

where $\vec{x}(\tau)$ is the displacement vector of MFP at the pseudo-time, τ ; $\vec{v}(\vec{x}(\tau), t_0)$ is the speed vector of the MFP at the desired time, t_0 .

Particle-paths are trajectories tracing or recording paths of individual particles over a certain period of time as they move in the direction and speed dictated by the local vector field. Particle-paths are obtained by integrating the following ordinary differential equation through real-time and using the actual time-varying values of velocity:

$$\frac{d}{dt} \vec{x}(t) = \vec{v}(\vec{x}(t), t)$$

where t is the time; $\vec{x}(t)$ and $\vec{v}(\vec{x}(t), t)$ are the displacement vector and speed vector of MFP respectively, at the time t .

Streak-lines, derived from time-varying vector fields, are the loci of all particles repeatedly releasing a sequence of particles from particular spatial points. It simulates experimental technique involving continuous release of tracer substances such as oil drops, smoke or dye. Computation of streak-lines takes more time because new MFPs are released at each time step.

Streamlines, particle-paths and streak-lines provide useful visualization of complex vector fields in aircraft cabins. Streamlines, particle-paths and streak-lines are exactly the same for steady vector fields, but quite distinct for unsteady vector fields. Streamlines can help visualize instantaneous vector fields, but reveal nothing of how vector fields change over a period of time. Particle-paths give a comprehensive view of how vector fields changed over time in regions covered by particles. Streak-lines provide a useful compromise between streamlines and particle paths, and provide intuitive

Fig. 1 (a) Experimental setup for PIV measurement (Cao et al. 2014). (b) Experimental setup of the aircraft cabin model. Typical surface 1 (TS1) and typical surface 2 (TS2) are the cross sections of the manikins' legs and manikins' bodies, respectively, within the fourth row. The size of rectangle measured region (RMS) by PIV is 975 mm $\times$ 650 mm within TS1. (c) The fourth row cabin model for LES (Yang et al. 2016), symmetric with the middle plane. Airflow around the aisle region has been emphasized in this study

physical analogy.

LES data provided detailed information on vector direction and magnitude in concerned regions. Based on simulated velocity fields with LES (Yang et al. 2016), the commercial software Tecplot 360 2013R1 was used to calculate particle-paths and streak-lines of MFPs. For unsteady velocity field, linear interpolation was performed between solution time levels, 0.01 s. Each particle was integrated until the final time level was reached or until the particle passed out of solution domain. When calculating MFPs' particle-paths and streak-lines, it can be thought of recording paths or trajectories of MFPs in the flow over a certain period because MFPs always travel with local fluid velocity. More information about methods for calculating streamline, particle path and streak-line can be found in (Bellevue 2013).

Bourouiba et al. (2014) proposed that smaller droplets (less than 50 μm diameter) from human coughs and sneezes can remain suspended in the cloud long enough. A droplet of diameter $d = 10 \mu\text{m}$ evaporates in 0.027 s, during which it would fall a distance of approximately 0.08 mm. It would thus clearly remain suspended in a cough sneeze cloud metres away from the cougher. Moreover, such small droplets or their associated droplet nuclei can be re-suspended by ambient air currents.

Wells (1934, 1955) proposed that drops with diameters larger than 100 μm , showed no significant evaporation as they settled on the ground in less than 1 s. While drops with diameters smaller than 100 μm became droplet nuclei before settling. Droplets with diameters smaller than 5–10 μm rapidly evolve into droplet nuclei with settling speeds of less than 3 mm/s, and may be readily suspended and driven by any ambient flow with long-range airborne transmission.

Coughing and sneezing release multiphase turbulent flows that are generally composed of buoyant hot moist air and suspended droplets of various sizes. These droplets contain various components such as pathogens and minerals that can form droplet nuclei after evaporation. The droplet size distribution for coughs with a peak drop size of 15 μm (Bourouiba et al. 2014). The pathogen-bearing solid residues of size smaller than 5–10 μm (referred to as droplet nuclei) can form from small droplets via evaporation (Bourouiba et al. 2014). Airborne transmission may arise through these droplet nuclei.

The droplet nuclei terminal settling velocity, V , can be evaluated by the following equation (Crowder et al. 2002):

$$V = \left(\frac{gC_c}{18\mu} \right) \rho_p d^2$$

where, d is the particle diameter, C_c is slip correction factor, g is the acceleration due to gravity, μ is the viscosity of air and ρ_p is the particle density.

For particle of diameter $d = 10 \mu\text{m}$, $C_c = 1.0172$, $\mu = 1.8 \times 10^{-5} \text{ Pa}\cdot\text{s}$, $\rho_p = 10\rho_{\text{air}}$ (assume the density of particle is ten times the density of air). Then the droplet nuclei terminal settling velocity can be obtained:

$$V \approx 3.7 \times 10^{-4} \text{ m/s} = 0.37 \text{ mm/s}$$

The terminal settling velocity is very small. The aerodynamic drag force is the dominant factor in the dynamics of particles in air and the mass is negligible.

This paper does not discuss the complicated movement or settling of large scale particles. However, the distribution and trajectories of small particles of diameters smaller than 10 μm with negligible mass within aircraft cabin, namely marked fluid particles, were investigated. This strategy is very helpful in studying instantaneous flow pattern of airflow within aircraft cabin mock-up as it is easy acquisition of airflow dynamics.

3 Results and discussion

3.1 Mean airflow patterns and characteristics

Velocity field in an aircraft cabin is usually analyzed by statistical averaging to obtain the airflow's mean characteristics in practical fluid dynamics. Figures 2(a1) and (a2) depict the statistically averaged velocity fields of LES in planes TS2 and TS1, respectively, the cross-sectional planes through the manikins' bodies and manikins' legs in the fourth row. The total statistical time is 103.2 s, including about 6 quasi-period airflow's large-scale unsteadiness. It can be seen that airflows from two opposing cabin sides collide in the middle of the cabin. Cabin environment is divided into two main domains by the ventilation system. There are two large scale vortices located on each side of the cabin (as shown in Fig. 2(a2)). Velocity fields in TS1 and TS2 are more or less symmetrical with the middle plane on the whole. The root mean square value of fluctuating velocity values is an important indicator of velocity field's unsteadiness, as seen from the statistical analysis process (Tamás et al. 2005). Information on turbulence intensity has been included implicitly. The velocity component's root mean square in directions X, Y and Z within TS1 and TS2 are presented in Figs. 2(b1), (b2), (b3), (c1), (c2) and (c3). It can be seen that around the aisle region, all root mean square values of velocity components appear obviously larger than others. It indicates that around the aisle region velocity fields are less steady and airflow structures are more complicated than others. Results of all integral characteristics are obtained through statistical averaging and root mean square of velocity field. However, there is little information on real instantaneous airflow structures and the airflow's time evolution. For highly unsteady or

Fig. 2 Statistical averaged mean velocity fields in TS2 (a1) and TS1 (a2) with LES. Root mean squares of the velocity components X (b1), Y (b2) and Z (b3) in TS2. Root mean squares of the velocity components X (c1), Y (c2) and Z (c3) in TS1. The statistically averaged time is 103.2 s

unstable velocity field, instantaneous flow fields are probably quite different from the ensemble averaging velocity fields obtained. More importantly, the impact of highly unsteady instantaneous velocity field on contaminant transmission must also be evaluated.

3.2 Temporal and spatial instability of airflow

The fine, instantaneous details of airflow are getting more important to be determined for better understanding of the instability mechanism of velocity field and contaminant transmission mechanism within aircraft cabin. The LES and PIV measurements, with full instantaneous velocity field within a time period, provide more instantaneous details of the velocity field (Cao et al. 2014; Yang et al. 2016). For better understanding of instability mechanism and contaminant transmission within this aircraft cabin mock-up, the instantaneous real airflow structures and patterns have been extracted from the acquired LES dataset in this research. Figure 3(a) shows the spatial velocity distribution along coordinate $X = 0$ within TS1 during period of time, 103.2 s. Figure 3(b1) shows the temporal fluctuation of instantaneous velocity component in X direction at point A ($X = 0$ m, $Y =$

1.5 m) within TS1 during period of time, 103.2 s. The instantaneous velocity component has been divided into three terms: $U_x(x, t) = \langle U_x(x, t) \rangle_c + \langle U_x(x) \rangle_p + u'_x(x, t)$. The first term, $\langle U_x(x, t) \rangle_c$, is the long time mean term, by definition independent of time (Fig. 3(b2)). The second term, $\langle U_x(x) \rangle_p$, is the quasi-periodic large scale term, time-averaged with per 1 s. It can also be interpreted as contribution of coherent modes to flow dynamics (Fig. 3(b3)). The third term is the turbulent fluctuation term (Fig. 3(b4)). It can be found that the velocity field around the aisle region is highly unsteady. There is obviously quasi-periodic large-scale unsteadiness of airflow around the aisle region.

Figures 4(a) and (b) compare the simulated instantaneous airflow patterns in TS1 with corresponding experimental results. Due to obstacles of seats and manikins, airflow pattern in TS2 could not be obtained in the experiment. The typical instantaneous airflow patterns in TS1 within aircraft cabin mock-up have been characterized. As shown in Figs. 4(a1), (a4) and (a5), there are three main airflow patterns of instantaneous velocity fields in TS1, which describe the main quasi-periodic unstable airflow structures around the aisle region. Initially, jet flows from two opposing sides of aircraft cabin collide in the middle plane within the cabin.

Fig. 3 (a) Spatial velocity distribution along coordinate $X = 0$ within TS1 during period of time, 103.2 s. (b1) Temporal fluctuation of instantaneous velocity component in X direction at point A ($X = 0, Y = 1.5$) within TS1. (b2) Long time mean term. (b3) Quasi-periodic large scale term. (b4) Turbulent fluctuation term

Then, due to the influence of various efficient perturbations such as small unequal air velocities of jets on either side or fluctuation of plumes produced by heated manikins, the collision position will move either left or right (as shown in Figs. 4(a2), (a3), (b2) and (b3)). Within seconds of airflow development, Pattern A transforms into Pattern B (or Pattern C). In Pattern B (or Pattern C), more air moves across the middle plane and enters the opposite side of the aircraft cabin. The left (or right) large-scale vortex is strengthened as the airflow swings left (or right), while at the same time, the right (or the left) large vortex is weakened. After one or several complicated bifurcations and in the final stage, Pattern B (or Pattern C) transforms into Pattern A. The next quasi-periodic airflow pattern switch begins again. Figures 4(b1), (b4) and (b5) are the corresponding PIV results. The computed airflow patterns agree qualitatively with the PIV experimental results. Figure 4(c) shows the corresponding main schematic diagram of instantaneous

airflow patterns. As various sufficient perturbations inevitably and randomly exist in LES simulation and PIV measurements, the high unsteadiness of velocity field around the aisle region continuously progresses, with the switch among three typical airflow patterns having certain randomness. The quasi-periodicity of airflow pattern around the aisle region is about 10–30 s. Li et al. (2016b) provided the instantaneous U -velocity at typical points, $XY (-0.050, 1.447)$, with approximate boundary conditions within same aircraft cabin. The quasi-periodicity of airflow pattern in this paper is very close to the research results by Li et al. (2016b).

According to the Peixoto theorem (Peixoto 1962), when a vector field is structurally stable, the necessary and sufficient conditions are that (Yang et al. 2016; Peixoto 1962): (1) there is only a finite number of generic singularities; (2) the α and ω -limit sets of every trajectory can only be singularities or closed orbits; (3) no trajectory connects saddle points; and (4) there are only a finite number of

Fig. 4 (a) Main airflow patterns obtained from LES. (b) Main airflow patterns obtained from homologous PIV experimental measurement (Cao et al. 2014; Yang et al. 2016). Small black arrow lines are velocity vectors. (c) Schematic diagram of large scale airflow patterns correspond to main airflow patterns. (a2), (a3), (b2), (b3), (c2) and (c3) are intermediate states during the pattern switch. (d) The Peixoto theorem: Pattern A, there are one saddle point (SP), two half saddle points (HSPs) and two heteroclinic orbits in TS1. Velocity field is not stable

closed orbits, all simple. In Pattern A, one saddle point (SP), two half saddle points (HSPs) and two heteroclinic orbits (connecting the SP and two HSPs) exist in TS1 as structural stability analysis (Fig. 4(d)). According to Peixoto theorem's third condition, this velocity field is not a structurally stable system. A small perturbation can destroy the heteroclinic orbit and cause complicated switch of patterns, such as from Pattern A to Pattern B. The Peixoto theorem interprets this temporal instability of airflow patterns within this single-aisle aircraft cabin mock-up. There is no fixed period between switches in typical airflow patterns. In general, 10–30 s are

needed to complete a quasi-periodic bifurcation of airflow.

Apart from the temporal instability of airflow patterns, there is also spatial instability of velocity field at a fixed advancing time in numerical calculation. As shown in Figs. 5(a), (b), (c) and (d), at the advancing time $t = 58.9$ s, velocity fields of LES and schematic diagram of large scale airflow patterns in three cross sections ($Z_1 = Z_{TS1} - 0.2$ m, $Z_0 = Z_{TS1}$ and $Z_2 = Z_{TS1} + 0.2$ m) of aircraft cabin mock-up were extracted. It can be seen that airflow patterns in cross sections Z_0 , Z_1 and Z_2 , are Pattern A, Pattern C and Pattern B respectively. In other words, airflow patterns in these three

Fig. 5 Airflow's spatial instability at advancing time $t = 58.9$ s of LES. (a) Positions Z_1 , Z_0 and Z_2 in the fourth row. (b) Velocity field, streamlines (black lines) and airflow patterns (pink lines) at $Z_1 = Z_{TS1} - 0.2$ m. (c) Velocity field, streamlines (black lines) and airflow patterns (pink lines) at $Z_0 = Z_{TS1} = 3.049$ m. (d) Velocity field, streamlines (black lines) and airflow patterns (pink lines) $Z_2 = Z_{TS1} + 0.2$ m

different cross sections along coordinate Z are different. The reason for this phenomenon is that small perturbations are generated, and progress differently in these three cross sections. Pattern A, Pattern B and Pattern C can exist simultaneously at the advancing time t but in different cross sections, which indicates that velocity fields are spatially unstable.

Figures 6(a) and (b) show the process of temporal and spatial instability of airflow and bifurcation process in this single-aisle cabin. For example, as shown in Fig. 6(a), at t_0 , the airflow patterns in cross sections Z_1 , Z_0 and Z_2 are Pattern B, Pattern A and Pattern C, respectively. According to the Peixoto theorem, this velocity field in Z_0 cross section is not a structurally stable system. A small perturbation can cause a complicated bifurcation. At $t_0 + \Delta t$, Pattern A in Z_0 cross section transforms into Pattern C. Due to low airflow velocity within aircraft cabin and the fact that it is also not rarefied air, continuum hypothesis of air is applicable in this study. Therefore, a new Pattern A, which is still a structurally unstable system, will inevitably generate in Z_3 cross section, where ($Z_1 < Z_3 < Z_0$). A new bifurcation will continue, once again generating a new Pattern A. Figure 6(c) shows velocity field and airflow pattern in $Z_3 = Z_{TS1} - 0.14$ m, $t = 61.05$ s. Figure 6(b) shows another similar bifurcation. Figure 6(d) shows velocity field and airflow pattern in $Z_4 =$

$Z_{TS1} + 0.16$ m, $t = 87.18$ s. On the one hand, looking at cross section $Z = Z_0$, it can be found that velocity fields at t_0 and $t_0 + \Delta t$ have different airflow patterns, similar to that shown in Fig. 3. This is the velocity field's temporal instability within this single aisle aircraft cabin. On the other hand, looking at $t = t_0$, it can be found that velocity fields in cross sections Z_0 , Z_1 and Z_2 have different airflow patterns. This is the velocity field's spatial instability within this single aisle aircraft cabin. Both temporal and spatial instability of velocity fields exist within this cabin mock-up.

3.3 Unstable velocity field's transport properties

A large number of small droplets or micro-particles (residue of evaporated small droplets) from sneezing, coughing and breathing by sick passengers are readily suspended in the expiratory area of the passengers (Bourouiba et al. 2014) within aircraft cabin and then carried by any ambient flow with long-range airborne transmission. Li et al. (2016a) had set the source of tracer gas in the manikin's expiratory area to analyze how airflow patterns affect contaminant transport in a single-aisle aircraft cabin mock-up. In this study, the MFPS were also released from the passenger's expiratory area to study the dynamics of unstable velocity field's transport properties within this single-aisle aircraft cabin

Fig. 6 Spatial instability and bifurcation. $Z_1 < Z_3 < Z_0 < Z_4 < Z_2$. (a) Pattern A in Z_0 transforms into Pattern C and a new Pattern A is generated in Z_3 . (b) Pattern A in Z_0 transforms into Pattern B and a new Pattern A is generated at Z_4 . (c) Velocity field, streamlines (black lines) and airflow patterns (pink lines) at $Z_3 = Z_{TS1} - 0.14$ m, $t = 61.05$ s. (d) Velocity field, streamlines (black lines) and airflow patterns (pink lines) at $Z_4 = Z_{TS1} + 0.16$ m, $t = 87.18$ s

mock-up. Due to the long computing time and high computational costs, only the fourth row LES data is available (Yang et al. 2016). The fourth row data was duplicated twice and a three-row aircraft cabin was created. The focus was on the transport characteristics of MFPs within the fourth row. By calculating particle-paths and streaklines of individual MFPs using Tecplot 360 2013R1, distribution and trajectories of MFPs released at different locations in exhalation area for a period of 40 stochastic seconds were obtained.

The Cartesian coordinates for three released MFP locations are S1 (−1.475, 1.2, −3.05), S2 (−0.96, 1.2, −3.05) and S3 (−0.455, 1.2, −3.05), in front of each manikin's breathing zone. Each pollution source is at a 50 cm distance from the nearest passenger's nose. Figures 7(a1), (a2), (a3), (b1), (b2), (b3), (c1), (c2) and (c3), display MFPs' distribution through continuous release from three independent sources for 40 s. 200 MFPs were released into the velocity field at releasing rate of 5 MFPs per second, with zero momentum, to avoid affecting the airflow. Distributions of MFPs continuously released from source S3 for 40 s at different releasing rates, namely 1 MFP per second, 3 MFPs per second, 5 MFPs per second and 7 MFPs per second are computed. As shown in Table 1, the percentages among first three

releasing rates are quite different. However, the difference between releasing rates 5 MFPs per second and 7 MFPs per second is very small. Therefore, in order to reduce amount of calculation and save calculation time, the study adopts the releasing rate, 5 MFPs per second, to obtain the distributions of MFPs and particle-paths of MFPs.

Table 2 gives the distribution of MFPs through continuous release from three independent sources, for 40 s. Obviously, the transmission of MFPs within this aircraft cabin mock-up is not isotropic, due to obstacles in seats and manikins, and distribution of inlets and outlets. Figure 8 shows the schematic diagram of MFPs' transmission approaches. It can be seen that due to airflow's swing motion around the aisle region, percentages of MFPs across the middle plane and invading into the opposite side of aircraft cabin are as much as 21%, 19% and 12%, with homologous MFP release sources located at S1, S2 and S3, respectively. It means that due to airflow's swing motion around the aisle region, passengers seated at opposite sides of aircraft cabin are potentially at risk of contracting MFPs released at S1, S2 and S3. The airflow's swing around the aisle region has great effect on transmission of MFPs. The percentages of $N_{1s1} > N_{1s2} > N_{1s3}$ are the influence of the large-scale vortex on MFPs transmission. In other words, this is also

Fig. 7 Distribution of air elements released from different pollution sources for a period of 40 seconds. Pollution source coordinates are (a1, a2, a3) S1: $(x, y, z) = (-1.475, 1.2, -3.05)$, (b1, b2, b3) S2: $(x, y, z) = (-0.96, 1.2, -3.05)$ and (c1, c2, c3) S3: $(x, y, z) = (0.455, 1.2, -3.05)$

Table 1 Distribution of MFPs continuously released from source S3 for 40 s at different releasing rates

Releasing rates	1 MFP per second	3 MFPs per second	5 MFPs per second	7 MFPs per second
Total number of MFPs released	40	120	200	280
Number (percentage) of MFPs across the middle plane	3 (7.5%)	11 (9.2%)	24 (12.0%)	32 (11.4%)
Number (percentage) of MFPs out of the fourth row	6 (15.0%)	17 (14.2%)	26 (13.0%)	35 (12.5%)
Number (percentage) of MFPs exhausting through outlets	5 (12.5%)	16 (13.3%)	31 (15.5%)	45 (16.1%)

Table 2 Distribution of MFPs continuously released from three independent sources for 40 s

Pollution sources	S1	S2	S3
Total number of MFPs released	200	200	200
Percentage of MFPs across the middle plane	N1s1: 21%	N1s2: 19%	N1s3: 12%
Percentage of MFPs out of the fourth row	N2s1: 13%	N2s2: 14%	N2s3: 13%
Percentage of MFPs exhausting through outlets	N3s1: 12%	N3s2: 7%	N3s3: 16%

Fig. 8 Schematic diagram of MFPs transmission approaches

the effect of MFPs release locations on MFPs transmission, when continuously released for a period of 40 s. The percentages of MFPs out of the fourth row are 13%, 14% and 13%, with homologous MFPs release sources located at S1, S2 and S3, respectively. Almost equal, these three percentage values indicate that locations of release sources have little effect on transmission of MFPs in the longitudinal direction. It also shows that MFPs transported in longitudinal direction are obviously smaller than that in latitudinal direction.

Percentage values of MFPs exhausting through outlets are 12%, 7% and 16%, with homologous MFP release sources located at S1, S2 and S3, respectively. N3s3 is much larger than N3s1 and N3s2; the reason being that part of MFPs released at S3, exhaust directly through outlets and not going along the large-scale vortex. N3s2 is much smaller than N3s1 and N3s3; the reason being that most of the MFPs released at S2, the central region of the large-scale vortex, have a similar influence to that of the carbon dioxide lockup phenomenon (Li et al. 2015) in aircraft cabin.

Distribution of MFPs at a fixed time cannot provide information on each MFP's trajectory during a period of time. By calculating each MFP's particle-paths, the transferring process and characteristics can be easily obtained. Figure 9 shows 5 typical transferring processes (Type A, Type B, Type C, Type D and Type E) of a MFP released at source S3 near the aisle region for 40 s. Figure 9(a) shows Type A: a MFP released at source S3, going along with the large-scale vortex at the same side of the cabin, and finally exhausting through outlet. Type A is mainly dominated by the large-scale vortex in the same side of source S3. For Type A, passengers of A, B and C are potentially at risk of being affected by the MFP released at S3. Figure 9(b) shows Type B: a MFP released at source S3, going across the aisle region, then going along with the large-scale vortex at opposite side of source S3, and finally exhausting through outlet. Type B is at first dominated by airflow's swing motion around the aisle region (Pattern B), and is then dominated by the large-scale vortex at the opposite side of the cabin. In Type B, passengers of D, E and F are potentially at risk of being affected by MFP released at S3. Figure 9(c) shows Type C, a more complicated transferring process than Type A and Type B: a MFP released at source S3, going across the aisle region, then going along the large-scale vortex on the opposite side of the cabin, then across the aisle region again, going along the large-scale vortex in the same side of S3, and finally exhausting through outlet. In Type C, the MFP goes across the aisle region at least once and goes along both large-scale vortices in the two sides of the cabin. All passengers in the fourth row are potentially at risk of being affected by MFP released at S3. As shown in Fig. 9(d),

in Type D, MFPs are transmitted out of the fourth row. Passengers seated in adjacent rows are potentially at risk of being affected by MFPs released at S3. This can be explained by the fact that longitudinal airflow inevitably exists within aircraft cabins, and contributes to the transmission of MFPs in the longitudinal direction. Figure 9(e) shows Type E: MFPs released at source S3, follow the strong downward airflow around the aisle region and leave directly from exhausts. No passengers are directly affected in Type E.

This study tracks and analyzes 300 trajectories of MFPs released at S3, at the rate of 5 MFPs per second and zero momentum, to generate a reliable statistical result during the first 60 s of the 103.2 s LES data. Each MFP's trajectory is transmitted within aircraft cabin for 40 s. More than 83% MFPs are transmitted out of the aircraft cabin mock-up, which shows that the integral time of 40 s to obtain path-lines and streak-lines in this research is appropriate.

Table 3 shows statistical percentages of Type A, Type B, Type C, Type D and Type E. Type A's percentage value (41%) is the largest, which indicates that passengers located at the same side of the cabin have the largest potential risk to be affected by the MFPs released at S3. The percentage values of Type B and Type C are 28% and 13%, respectively, which shows that the airflow's swing motion around the aisle region has great influence on the MFPs moving across the aisle region. It puts passengers seated at the opposite side of cabin at greater risk of being affected. Type D's percentage value is 5%, which indicates that when there is no movement by crew members, passengers and beverage carts, and there is only ventilated airflow, passengers seated in neighboring rows have 5% chance of being affected by MFP released at S3. Type E percentage is 13%, which means that 13% of MFPs are directly exhausted out of aircraft cabin mock-up, with no obvious impact on other passengers. In general, MFPs transported in latitudinal direction are obviously larger than in longitudinal direction. Complex geometries (passenger seats and heated manikins) and instantaneous airflow patterns (airflow's swing motion around the aisle region, large-scale vortices and longitudinal airflow) are tied together and make MFP transmission in the aircraft cabin extremely complex.

Contaminant transmission within aircraft cabin is a mixed effect of the airflow's swing motion around the aisle region, large-scale vortices and longitudinal airflow. The airflow's swing motion around the aisle region attempts to carry nearby contaminants nearby across the aisle region, and invades the opposite large-scale vortex. The two large-scale vortices try to control the released contaminants in each separated zone. At the same time, longitudinal airflow also tries to transmit contaminants to neighbouring rows.

Fig. 9 Transferring processes and path-lines of MFPs released from S3 for 40 s: (a) Type A; (b) Type B; (c) Type C; (d) Type D; (e) Type E

Table 3 Percentage values of 5 MFP transmission types for 300 trajectories during 40 s

Types	Type A	Type B	Type C	Type D	Type E
Percentage	41%	28%	13%	5%	13%

4 Conclusion

The main objective of this paper's investigation was to reveal velocity field's instantaneous characteristics, analyze instantaneous velocity field's temporal and spatial stability, and evaluate MFP transmission within the simplified B737-200 cabin model. Compared to the mean and root mean squares of velocity field, instantaneous velocity field can provide real detailed airflow structures and time evolution of instantaneous airflow patterns within aircraft cabin. This information is very important to understand the mechanism of the velocity field's continuing high unsteadiness and contaminant transmission within this aircraft cabin. The conclusion is as follows:

- 1) Instantaneous airflow within this cabin mock-up is inherently unstable, which characterizes this type of flow regime and geometry. Velocity field within this single-aisle cabin mock-up is both temporally and spatially unstable. A sufficient small perturbation could cause a series of complicated airflow bifurcations. The Peixoto theorem can be used to interpret this airflow instability.
- 2) Unstable instantaneous airflow within this single aircraft cabin has tremendous impact on MFP transmission. MFP transmission within this aircraft cabin is a mixed effect of airflow's swing motion around the aisle region, large-scale vortices and longitudinal airflow. The airflow's swing motion around the aisle region tends to carry MFPs nearby across the aisle region, and invades the opposite large-scale vortex. The large-scale vortices try to control the released MFPs in separated zones. Longitudinal airflow also tries to transmit contaminants to neighboring rows. Moreover, the airflow's swing motion around the aisle region and large-scale vortex dominate MFPs' latitudinal transmission, whereas longitudinal airflow dominates MFPs' longitudinal transmission.

Acknowledgements

The research presented in this paper was financially supported by the National Basic Research Program of China (The 973 Program) through grant no. 2012CB720100.

References

- Baker AJ, Ericson SC, Orzechowski JA, Wong KL, Garner RP (2006). Validation for CFD prediction of mass transport in an aircraft passenger cabin. Federal Aviation Administration, Washington, DC. AM-06/27.
- Bellevue W (2013). Tecplot User's Manual. Bellevue, WA, USA: Amtec Engineering Inc.
- Bourouiba L, Dehandschoewercker E, Bush JW (2014). Violent expiratory events: On coughing and sneezing. *Journal of Fluid Mechanics*, 745: 537–563.
- Cao X, Liu J, Pei J, Zhang Y, Li J, Zhu X (2014). 2D-PIV measurement of aircraft cabin air distribution with a high spatial resolution. *Building and Environment*, 82: 9–19.
- Crowder TM, Rosati JA, Schroeter JD, Hickey AJ, Martonen TB (2002). Fundamental effects of particle morphology on lung delivery: Predictions of Stokes' law and the particular relevance to dry powder inhaler formulation and development. *Pharmaceutical Research*, 19: 239–245.
- Ebrahimi K, Zheng ZC, Hosni MH (2013). A computational study of turbulent airflow and tracer gas diffusion in a generic aircraft cabin model. *Journal of Fluids Engineering*, 135: 11105.
- Garner RP, Wong KL, Ericson SC, Baker AJ, Orzechowski JA (2003). CFD validation for contaminant transport in aircraft cabin ventilation flow fields. In: Proceedings of Annual SAFE Symposium, Jacksonville, FL, USA, pp. 248–253.
- Gidaspow D (1994). Multiphase Flow and Fluidization: Continuum and Kinetic Theory Descriptions. New York: Academic Press.
- Hocking MB (1998). Indoor air quality: recommendations relevant to aircraft passenger cabins. *American Industrial Hygiene Association Journal*, 59: 446–454.
- Isern-Fontanet J, Font J, García-Ladona E, Emelianov M, Millot C, Taupier-Letage I (2004). Spatial structure of anticyclonic eddies in the Algerian basin (Mediterranean Sea) analyzed using the Okubo-Weiss parameter. *Deep Sea Research Part II: Topical Studies in Oceanography*, 51: 3009–3028.
- Li F, Liu J, Pei J, Lin C H, Chen Q (2014). Experimental study of gaseous and particulate contaminants distribution in an aircraft cabin. *Atmospheric Environment*, 85: 223–233.
- Li M, Zhao B, Tu J, Yan Y (2015). Study on the carbon dioxide lockup phenomenon in aircraft cabin by computational fluid dynamics. *Building Simulation*, 8: 431–441.
- Li F, Liu J, Ren J, Cao X, Zhu Y (2016a). Numerical investigation of airborne contaminant transport under different vortex structures in the aircraft cabin. *International Journal of Heat and Mass Transfer*, 96: 287–295.
- Li J, Liu J, Cao X, Jiang N (2016b). Experimental study of transient air distribution of a jet collision region in an aircraft cabin mock-up. *Energy and Buildings*, 127: 786–793.
- Lin CH, Horstman RH, Ahlers MF, Sedgwick LM, Dunn KH, Topmiller JL, Bennett JS, Wirogo S (2005). Numerical simulation of airflow and airborne pathogen transport in aircraft cabins—Part I and Part II. *ASHRAE Transactions*, 111(1): 755–763.
- Lin CH, Wu T T, Horstman RH, Lebbin PA, Hosni MH, Jones BW, Beck BT (2006). Comparison of large eddy simulation predictions with particle image velocimetry data for the airflow in a generic cabin model. *HVAC&R Research*, 12: 35–951.
- Liu W, Wen J, Chao J, Yin W, Shen C, Lai D, Lin C-H, Liu J, Sun H, Chen Q (2012). Accurate and high-resolution boundary conditions and flow fields in the first-class cabin of an MD-82 commercial airliner. *Atmospheric Environment*, 56: 33–44.

- Mangili A, Gendreau MA (2005). Transmission of infectious diseases during commercial air travel. *The Lancet*, 365: 989–996.
- Mazumdar S, Poussou SB, Lin CH, Isukapalli SS, Plesniak MW, Chen Q (2011). Impact of scaling and body movement on contaminant transport in airliner cabins. *Atmospheric Environment*, 45: 6019–6028.
- Nicoud F, Ducros F (1999). Subgrid-scale stress modelling based on the square of the velocity gradient tensor. *Flow, Turbulence and Combustion*, 62: 183–200.
- Okubo A (1970). Horizontal dispersion of floatable particles in the vicinity of velocity singularities such as convergences. *Deep Sea Research and Oceanographic Abstracts*, 17: 445–454.
- Olsen SJ, Chang H-L, Cheung TY-Y, Tang AF-Y, Fisk TL, Ooi SP-L, Kuo H-W, Jiang DD-S, Chen K-T, Lando J, Hsu K-H, Chen T-J, Dowell SF (2003). Transmission of the severe acute respiratory syndrome on aircraft. *New England Journal of Medicine*, 349: 2416–2422.
- Peixoto MM (1962). Structural stability on two-dimensional manifolds. *Topology*, 1: 101–120.
- Provenzale A (1999). Transport by coherent barotropic vortices. *Annual Review of Fluid Mechanics*, 31: 55–93.
- Spengler JD, Wilson DG (2003). Air quality in aircraft. *Proceedings of the Institution of Mechanical Engineers, Part E: Journal of Process Mechanical Engineering*, 217: 323–335.
- Tamás R, Rambaud P, Riethmuller ML (2005). Extraction of coherent structures from unsteady flows by means of POD. In: Proceedings of MICROCAD Conference.
- Trupka A, Hosni M, Jones BW (2011). Tracer gas and smoke flow visualization assessment of the impact of a beverage cart on contaminant dispersion in a twin aisle aircraft cabin. SAE Technical Paper Series. 2011-01-2692.
- Wells WF (1934). On air-borne infection. Study II. Droplets and droplet nuclei. *American Journal of Hygiene*, 20: 611–18.
- Wells WF (1955). Airborne Contagion and Air Hygiene. An Ecological Study of Droplet Infections. Cambridge, MA, USA: Harvard University Press.
- Yan W, Zhang Y, Sun Y, Li D (2009). Experimental and CFD study of unsteady airborne pollutant transport within an aircraft cabin mock-up. *Building and Environment*, 44: 34–43.
- Yang C, Zhang X, Yao Z, Cao X, Liu J, He F (2016). Numerical study of the instantaneous flow fields by large eddy simulation and stability analysis in a single aisle cabin model. *Building and Environment*, 96: 1–11.
- Zhang T, Li P, Zhao Y, Wang S (2013). Various air distribution modes on commercial airplanes. Part 1: Experimental measurement. *HVAC&R Research*, 19: 268–282.
- Zhang Z, Chen X, Mazumdar S, Zhang T, Chen Q (2009). Experimental and numerical investigation of airflow and contaminant transport in an airliner cabin mockup. *Building and Environment*, 44: 85–94.