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Turbulence characterization of instantaneous airflow in an aisle of an aircraft cabin mockup

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A B S T R A C T

The turbulence characteristics of instantaneous airflows in an aircraft cabin mockup are measured by high-frequency mini particle image velocimetry (mini-PIV) and analyzed by higher-order turbulent statistics. Under maxing ventilation in the aircraft cabin, two jets from the diffusers collide each other in the middle of the aisle. The airflows of collision regions in an aircraft cabin are typically turbulent, with a low velocity magnitude and a high fluctuation. Although the average airflow fields are uniform and have a smaller velocity gradient, the instantaneous airflow fields are remarkably unstable. Turbulence scales are utilized to analyze the spatial and temporal characteristics of the instantaneous airflows. The maximum airflow vortex scale of the collision zone is 11 cm, and the minimum vortex scale is only 8×10^{-4} m. The inertial sub region of the airflow power spectrum in the collision region is approximately 4–10 Hz. The wavelet coefficients of instantaneous fluctuation velocity have a quasi-periodicity of approximately 0.5 s, when the scale factor is 54. The grid size of direct numerical simulation (DNS) is recommended to be less than 0.3 mm, that of the large eddy simulation (LES) should be between 0.3 and 100 mm and that of the Reynolds-average Navier-Stokes (RANS) should be larger than 100 mm and smaller than the characteristic scale of airflows. The LES unsteady simulation time step should be less than 0.1 s, and the time step of RANS method should be less than 0.25 s. The power spectrum exponent of the instantaneous airflows in the aircraft cabin mockup is between 1.2 and 1.8, similar to natural wind, and will thus have a beneficial impact on human comfort.

1. Introduction

Under typical mixing ventilation system in the aircraft cabin, the mean air velocities range from below 0.05 m/s to 1 m/s with 60% velocities below 0.2 m/s, the turbulence intensities range from less than 10%–70%, and the characteristic frequencies of fluctuation velocity range from 1 Hz to 100 Hz. The airflows in an aircraft cabin are typically turbulent, with the velocities varying in magnitude, fluctuation frequency and quasi-periodic because of turbulent structural instability [1,2].

The average characteristics of the low-speed turbulent airflows in an aircraft cabin are commonly determined by experimental measurements and numerical modeling. PIV and an ultrasonic anemometer (UA) are applied to investigate airflow velocity, taking into consideration their advantages of low-speed measurements [3]. The mean velocity field and velocity root mean square (RMS) have been investigated by PIV with measuring frequency below 15 Hz in aircraft cabin mockups in many relevant research studies [4–7]. According to the Nyquist-Shannon sampling theorem, the sampling frequencies are too low to allow the analysis of the turbulent and temporally varying airflow characteristics [8]. Liu used 20 Hz ultrasonic anemometers to study the airflow distributions; however, they only focused on the average velocities and the turbulence intensities [2]. The hot-wire anemometer (HWA) has a sampling frequency that can reach 1000 kHz, which can extract the turbulent and temporal characteristics accurately. However, it cannot obtain the low-speed airflows accurately because the heated sensor is sensitive to velocity direction and generated thermal plume which will cause measurement errors [9]. Numerical simulations are widely used to analyze the overall airflows and contaminant transport in an aircraft cabin mockup. Significant numerical simulation research achievements enabled the airflows

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characteristic to be obtained using different numerical simulation method, such as DNS, LES and RANS. Only time-averaged airflow parameters, including mean velocities, turbulence intensities and RMS velocity fluctuation are studied [10–13].

However, airflows in an aircraft cabin are unsteady and quasi-periodic due to intensive jet collision and intermittent human thermal plumes under the mixing ventilation systems. Li et al. summarized three transient airflow patterns with the fluctuation period from 10 s to 30 s in an aircraft cabin mockup [14]. Simultaneously, Yang [15] studied the instability and bifurcation of airflow patterns by numerical simulation and found that an alteration of topological characteristics around the aisle region allowed the various amplitudes and frequencies. Moreover, the instantaneous airflow frequency and the spectral characteristics are sensitive to draft. Ryan and Tan [16]adopted several nonlinear indices, including phase space restructure map, information entropy and information dimension, to analyze different airflow fluctuant characteristics. They concluded that human draft sensation is closely correlated with the power spectrum exponent (β value), which varied for different airflows, such as natural wind and mechanical wind. The turbulent scale characteristics of instantaneous airflows affect not only the draft but also the contaminant transport in ventilated spaces. Li studied gaseous contaminants and particle distribution in an aircraft cabin mockup under a mixing ventilation system and found that unsteady airflows lead to a skewed distribution and turbulent large-scale eddies of trapped gases in vortex zones [17]. The turbulent characteristics of instantaneous airflow in the aircraft cabin mockup should be studied.

A large amount of numerical investigation is involved in describing the airflows in an aircraft cabin. However, identifications of the grid discretization, turbulence model, and time step as well as result validation were based on experience or assessed by the average airflow parameters. Most studies of aircraft cabin airflows have used a time step from below 0.1 s—10 s, according to experience [4,18]. Xu [19]calculated the time step in different turbulence models with stability time and statistical average time and analyzed the errors based on mean velocity a MD82 airflows research. In addition, grid discretization in Xu's numerical simulation of aircraft airflow was determined according to the grid independence test. However, they only rationalized grid quantity, not the grid scales, which were scattered between 3 mm and 10 cm under aircraft length. Liu [20] confirmed the minimum grid size based on the characteristic length of the air supply diffusers when he predicted the aircraft cabin airflows. Abundant predicted results were validated by experimental data, many of which were compared with velocity, RMS and turbulence intensity. In summary, the limitation of the numerical method required to be worked out by high-order airflow quantities, with the turbulence scales guiding the grid discretization, the characteristic frequency determining time step and the turbulent energy features support turbulence model option.

Therefore, our present research focuses on the high-order turbulent statistics of instantaneous airflows in an aircraft cabin mockup. In this study, we measure turbulent low-speed airflows using a mini-PIV with a sampling frequency 400 Hz, which is sufficient to meet the turbulent requirement. Statistical analysis, turbulent scales, energy spectrum and wavelet analysis are used to determine the airflow turbulent characteristics.

2. Experimental method

Instantaneous airflows are studied in a 7-row, single-aisle aircraft cabin mockup based on a Boeing 737-200 with mixing ventilation system. The cabin mockup supplies air from linear slot diffusers, each with a length are 50 mm and a width of 3.5 mm after the flow equalizing plates. In the cabin mockup, the personal air rate is 9.4 L/s per person, which complies with the ASHRAE standard [21] . Moreover, the air change rate of the 7-row cabin mockup is 41 per hour under the mixing ventilation condition. The temperature of supply airflows is 19 °C ± 0.5 °C according to the ASHRAE standard for human thermal comfort in the aircraft cabin. The wall temperature is controlled by a thermostatic chamber, with a target of 19 °C. Based on the above conditions, the supply air velocities are approximately 2 m/s, with little velocity components along length of the aircraft cabin mockup, and the turbulent intensities are up to 30%. Considering the human thermal plume, 42 heated manikins are seated in the 7-row cabin mockup with the heat of 75 W; each manikin is used to simulate a human occupant [22].

A comparison of the velocity in the 7-row cabin mockup between 2D-PIV and UA measurement results indicates that the velocities of the cross section located at the forth row of the cabin mockup have excellent two-dimensional performance [23] as shown in Fig. 1. The longitudinal velocities are too small and can be ignored. The pie chart shows the velocity magnitude distribution proportion, with almost 87% of the velocities being below 0.5 m/s as shown in Fig. 2. Only 1% of the velocities are higher than 1 m/s in the zone 0.2 m away from the airflow slots.

Considering the advantages of PIV airflow measurement, i.e., non-contact airflow field determination and accurate low-speed measurement if tracing particles following air perfectly. Meanwhile, high sampling frequency meets the requirement of analysis high-order turbulent quantity. Therefore, a mini-PIV system produced by Beiting fluid Co. Ltd. located in Beijing, China, was utilized to measure airflows in the cross section of the 7-row cabin mockup. The mini-PIV uses a continuous wave laser as a laser source with a maximum power 5 W. A PCO edge 5.5 CCD camera combined with a Canon 35 mm lens is used to record the images. The visual field of the CCD is 960 pixels × 520 pixels, with the size of the interrogation window of 32 pixels × 32 pixels and 50% overlap between each interrogation window [24]. After calculation, the field of view is 0.3 m × 0.15 m, with a spatial resolution of 5.3 mm. Atomizing diethylhexyl sebacate (DEHS) via a Laskin nozzle is the method used to produce the tracing particles, each of which has a diameter of approximately 1 μm, which allows the air to be followed perfectly.

Fig. 3 shows the measuring area schematic diagram in the 7-row

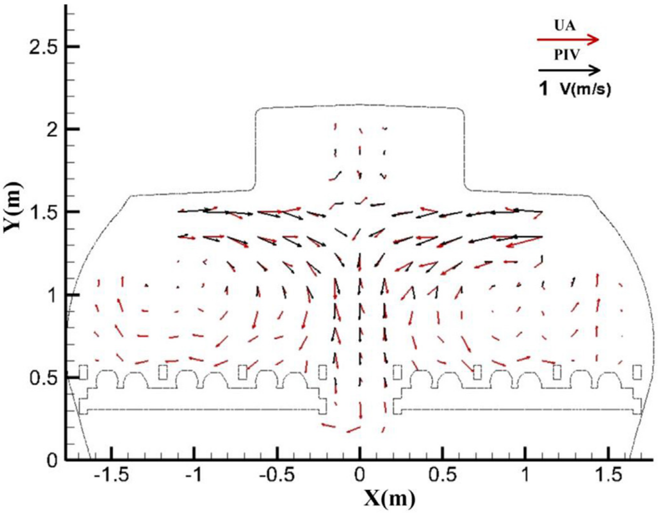

Fig. 1. Comparison of the velocities measured by PIV and UAs.