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Study on dynamic characteristics of natural and mechanical wind in built environment using spectral analysis

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Abstract

What are the differences and similarities between natural and mechanical wind in built environment? This is an interesting question that has not been well answered yet. In the paper, spectral analysis is applied to study the dynamic characteristics of natural and mechanical wind in different conditions. The results show that in the frequency region sensitive to human sensation, the power spectrum characteristics of natural wind and mechanical wind have obvious differences as well as interesting connections. The power spectrum exponent (β value) of natural wind is between 1.1 and 2.0 in the human sensitive frequency region, while the value of mechanical wind is between 0 and 0.5 around the air supply outlet. With the diffusion of mechanical wind, β value will increase gradually and reach the value of the typical natural wind when the mean velocity is lower than 0.25 m/s. Finally, the influence of spectral characteristics on human sensation for airflow is discussed.

Keywords: Built environment; Natural wind; Mechanical wind; Thermal comfort; Spectral analysis

1. Introduction

The use of air conditioning systems in indoor environment has caused a lot of complaints of discomfort, despite the fact that design of these systems follows the code. On the other hand, people find that natural ventilation tends to be more pleasant and acceptable. Apart from energy savings and improved air quality, the fact that natural ventilation is favorable to human thermal comfort is another important reason. Many field surveys [1–4] have showed that in naturally-ventilated buildings, the comfortable air temperature is higher than that of air-conditioned buildings and the natural wind with relatively high mean velocity is more acceptable than mechanical wind at the same velocity. Why? The adaptability of human beings to nature is formed by thousands of years of their evolution in the nature, and this long process determines that humans have better acceptability for natural environment. Thus, people should have normal physiological basis to adapt to the fluctuant natural wind. On the other hand, mechanical wind is just one of the results of industrial revolution, and its development history is just 100 years or so and cannot be compared with the history of human evolution. The sustainable development direction of artificial built environment should be adaptive to human nature, not the reverse. However, what are the major differences and connections between natural and mechanical wind? What factor influences the different sensation of natural and mechanical wind? These are very interesting problems but have not been deeply investigated.

Research has shown that the acceptability of human to wind is connected closely to the stimulus of airflow on the surface of skin and the information transferred to the brain, as well as the factor of heat transfer [5]. So the dynamic characteristics of airflow should be carefully considered. Power spectral analysis is one of the most

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important methods to study the dynamic characteristics of airflow, which is widely used for information analysis and turbulence research. In the 1980s, the Japanese researchers began to use power spectral analysis to study the outdoor natural wind and found the fluctuant velocity of natural wind has $1/f$ fluctuations property [6,7]. The $1/f$ fluctuations are ubiquitous in nature and have close relationship with people's pleasure [8]. Meanwhile, other researchers also adopted stochastic analysis method to study the dynamic characteristics of airflow in air-conditioned or mechanically ventilated rooms [9–11]. The analytical parameters included turbulence intensity, standard deviation, turbulent integral scale, correlation and spectral characteristics. However, none of the above researchers investigated the difference and connection between natural and mechanical wind from the view point of spectral characteristics. In this paper, the spectral characteristics of natural wind and mechanical wind in different conditions were measured and analyzed. The results show that in the frequency region which is sensitive to human sensation, the spectrum characteristics of natural and mechanical wind in built environment have obvious differences and interesting connections. Based on the above findings, the influence of spectral characteristics on human sensation for airflow is discussed.

2. Analysis method

According to the turbulence theory, the turbulent flow can be regarded as the superposition of eddies of different scales. The power spectral density function in spectral analysis can give the relationship between frequency and its corresponding energy of different eddies, which can show the energy distribution in a certain frequency range so that the dynamic characteristics of the flow field can be shown roundly. The instantaneous velocity (v) can be assumed to be the sum of the mean velocity ($\bar{v}$) and the velocity fluctuations (v'), and the power spectrum density function $E(f)$ meets the following equation:

$$\int_0^\infty E(f)\,\mathrm{d}f = \overline{v'^2}, \tag{1}$$

where f is the frequency (Hz).

For the discrete sample function, the discrete frequency is always selected as:

$$f = \frac{n}{N \cdot \Delta t}, \quad n = 0, 1, 2, \ldots, N-1, \tag{2}$$

where N is the total number of sample data, and Δt is the sampling interval (s).

The discrete power spectrum density function $E(n)$ is calculated by

$$E(n) = \frac{2\Delta t}{N}|X(n)|^2 = \frac{2\Delta t}{N} X^*(n)X(n). \tag{3}$$

$X(n)$ is the Fast Fourier Transfer (FFT) of sample data $X(t)$ of instantaneous velocity, and $X^*(n)$ is conjugate complex number of $X(n)$.

Fig. 1 shows the typical logarithmic power spectrum curves of natural wind in the outdoor open area and mechanical wind around the air supply outlet. It is found that the negative slope (β value) of the curves of natural and mechanical wind is obviously different.

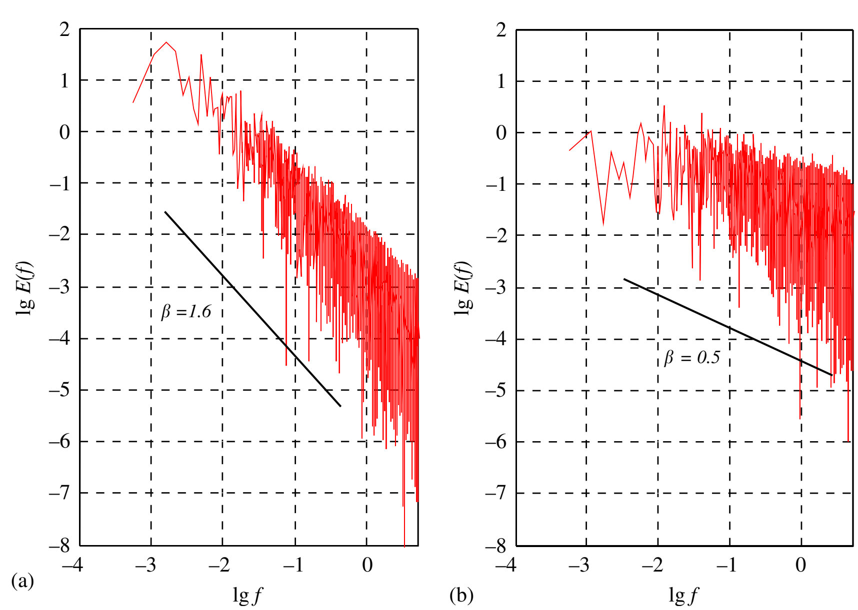

Fig. 1. The typical logarithmic power spectrum curves of (a) natural wind and (b) mechanical wind.