Study of cross- ventilated indoor air flow characteristics by frequency analysis

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Abstract
In Japan where is located at the hot humid climate region, houses have been built considered hot summer life from ancient times. It is said that comfortable and cool feelings by cross-ventilation were more important. However, the characteristics of cross-ventilated air flow are unclear, and that it has yet to be revealed how they affect the psychological and physiological factors that influence comfortable feeling. So, in this study, time-series data of cross-ventilated indoor air flow velocity were measured by field measurement at the actual detached house in Japan. Various turbulence statics of cross-ventilated indoor air flow were investigated by with frequency analysis (FFT). As a result, they were observed that wind velocity, eddy size and power spectrum configuration are different in and out of the cross-ventilated air flow pathway.

Keywords: Cross ventilation, Air flow characteristic, Turbulence static, Wind velocity, Turbulent velocity, Power spectrum, Characteristic time, Eddy size, Frequency analysis

Introduction

In Japan where is located at the hot humid climate region, houses have been built considered hot summer life from ancient times. It is said that comfortable and cool feelings by cross-ventilation were more important. Recently, the momentum of incorporating outdoor air into the house by cross-ventilation in good time of ambient conditions as summer night from the view point of energy saving. However, the characteristics of cross-ventilated air flow are unclear, and that it has yet to be revealed how they affect the psychological and physiological factors that influence comfortable feeling. So, in this study, time-series data of cross-ventilated indoor air flow velocity were measured by field measurement at the actual detached house in Japan and investigations about cross-ventilated indoor air flow characteristics were carried out taking temporal and spatial fluctuation of observed data by three-dimensional ultrasonic anemometer into consideration. In particular, various turbulence statics[1] of cross-ventilated indoor air flow were investigated by analysis of observed air flow data using frequency analysis[2] (FFT).

Measurement Method

Fig. 1 shows the overview of detached house to be measured. The house is suburban two-storied building in Noda city, Chiba prefecture, Japan. The measurement was performed in July, 2009. Fig. 2 shows the surrounding buildings of the house. South side and east side of surveyed house are bordered by road. There are plan and section of that house in Fig. 3. The room where measurement was carried out is southeast one. For the measurement of indoor air flow velocity, nine ultrasonic anemometers were set up on a plane in Fig. 3. The ultrasonic anemometer probes were adjusted at 1100mm height above the floor and the time interval for data collecting is 0.1 second. Also, outdoor wind velocity and wind direction were measured on the roof of detached house. Indoor air flow in about 20 seconds when the wind velocity and wind direction on the roof were stable became the target of the frequency analysis (FFT). Fig. 4 and Fig. 5 show the time-series data of outdoor wind velocity and wind direction investigated.

Analysis Method

Turbulent flow field consist of many different size air cloud are called eddy. Eddies possess properties differing from surrounding air and behave in a group. It is thought that various physical quantities such as wind velocity are similar to each other in same eddy. Many eddies move with respect to one another randomly on the mean flow and the fluctuation of air flow are generated. Therefore it is thought that fluctuation of air flow depend to a large part on the size and the mean velocity of eddy. There are turbulent velocity, eddy size and characteristic time and so on as these turbulence statics of air flow. Here are analysis methods in this study. The power spectrum displayed with respect to each frequency of indoor air flow is derived from measured wind velocity data by fast Fourier transformation. Then, the autocorrelation function is computed by the inverse Fourier transformation. And that the characteristic time is calculated from the autocorrelation function result. The outlines of turbulence statics definition for in this study are showed as described below.

Synthesized wind velocity: This wind velocity is synthesized in consideration of three-dimensionality from unidirectional wind velocity component of X, Y and Z directions as described Eq.1.

$$V = \sqrt{V_X{}^2 + V_Y{}^2 + V_Z{}^2} \qquad \text{(Eq. 1)}$$

V : Synthesized wind velocity (m/s), V_X : Wind velocity of X direction (m/s), V_Y : Wind velocity of Y direction (m/s), V_Z : Wind velocity of Z direction (m/s)

The wind velocity in this study is indicates synthesized wind velocity.

Turbulent velocity: It is thought that measured wind velocity V is broken down to time averaged wind velocity $\overline{V}$ and fluctuating wind velocity v as described Eq.2.

$$V = \overline{V} + v \qquad \text{(Eq. 2)}$$

$\overline{V}$: Time averaged wind velocity (m/s), v : Fluctuating wind velocity (m/s)

The standard deviation of fluctuating wind velocity v is called turbulent velocity.

Characteristic time: Characteristic time is the time scale individualize turbulent flow field. The time scale represents the averaged time when they are in the same eddy or the time when eddy pass a certain one point. Therefore, characteristic time is considered a time which retain correlation that autocorrelation function is 1 such as Fig.6 and is described as Eq.3.

$$T = \int_0^{\tau_0} R(\tau)\, d\tau \qquad \text{(Eq. 3)}$$

T : Characteristic time (s), τ : Elapsed time (s), $R(\tau)$: autocorrelation function, τ_0 : Elapsed time that autocorrelation function become 0.

Eddy size: Eddy size is described as Eq.4 and it is expressed as a product of mean wind velocity and characteristic time. This indicates length scale of turbulent flow fields.

$$A = \overline{V} \times T \qquad \text{(Eq. 4)}$$

A : Eddy size (m)

Wave number: Wave number is an indicator of eddy number per unit length. If the eddy is on the mean flow, it is thought that the frequency is influenced by the mean wind velocity. Wave number k is obtained by the removal of the effect of mean wind velocity (Eq.5).

$$K = \frac{2 \times \pi \times n}{\overline{V}} \qquad \text{(Eq. 5)}$$

K : Wave number (rad/m), π : Circular constant, n : Frequency (Hz)

Results and Discussion

Fig.7 and Fig.8 show the time-series data of wind velocity of indoor air flow in analysis object time. Each measurement point is divided into that in the cross-ventilated air flow pathway or that out of pathway groups from synthesize wind velocity result. The tendency that change in wind speed is different between the both is clearly observed.

Fig.9 shows the power spectrum displayed with respect to each frequency. There is the fluctuation form as general characteristics. There is the about hundredfold difference of energy between points A and B lie near opening window. There is the about tenfold difference of energy between points D and E lie near the center of the room. However, there is the little difference of energy between points G and I lie near the outlet of indoor air flow.

Fig.10 shows the cumulative frequency distribution of the power spectrum displayed with respect to each frequency. In the low-frequency region, the tendency that the power spectrum energy out of cross-ventilated air flow pathway is lower than that on the pathway is observed. However, remarkable difference was not observed except point A.

Fig.11 shows the cumulative frequency distribution of the power spectrum displayed with respect to each wave number. In the result displayed with respect to each wave number, there is remarkable difference between air flow on pathway and that out of pathway as compared with the result displayed with respect to each frequency. Eddies those size are up to 10 [rad/m] make up about from 30 to 60 percent of the whole at the point A and point D. However, they make up about 95 percent of the whole at the point B and point E. There is remarkable difference in the depth direction from opening window in the room. Eddies those size are up to 1 [rad/m] make up about 60 percent of the whole at the point B lie in front of the window. However, they make up about 40 percent of the whole at the point E lie near the center of the room and about 25 percent of the whole at the point I lie near the outlet of indoor air flow. From above results, the tendency that large size eddies are dissipated as heat converting to small size eddies as going to back of the room can be observed. Eddies those size are over 100 [rad/m] are observed and mean wind velocity is small in the region out of the cross-ventilated air flow pathway. From above results, it is found that very small size eddies remain in that place.

Table 1 shows the results of turbulence statics such as turbulent velocity, characteristic time and eddy size. Eddy size in the cross-ventilated air flow pathway are about from 0.2 [m] to 0.8 [m], but they are about from 0.02 [m] to 0.09 [m] out of the cross-ventilated air flow pathway. There are remarkable differences between in and out of cross-ventilated air flow pathway.

Conclusions

In this study, cross-ventilated air flows were measured by three-dimensional ultrasonic anemometer and investigation about indoor air flow characteristics were carried out by frequency analysis (FFT). Some turbulence statics such as eddy size were adopted as evaluation index. Cross-ventilated air flow pathway was assumed by measured wind velocity results and the differences of turbulence statics between air flow in the pathway and that out of the pathway. Investigations of the turbulence statics change along the cross-ventilated air flow pathway were carried out. As a result, there were differences in characteristic time and power spectrum in addition to wind velocity between the air flow in cross-ventilated air flow pathway and that out of the pathway. There is remarkable difference in the power spectrum displayed with respect to each wave number and the tendency that large size eddies of indoor air flow are dissipated converting to small size eddies as going to outlet of air flow from opening window. For the future, the measurement and the investigation of air flow characteristics which cross the opening window will be occurred.

References

1. Nobuyuki Kobayashi, “Basic study about the air flow characteristics of closed space”, Doctoral thesis, The University of Tokyo, 1974.

2. Yorihiko Osaki, “Approach of spectral analysis for earthquake motion, New edition”, Kajima Institute Publishing, 1994.

Fig. 1 Overview of detached house to be measured

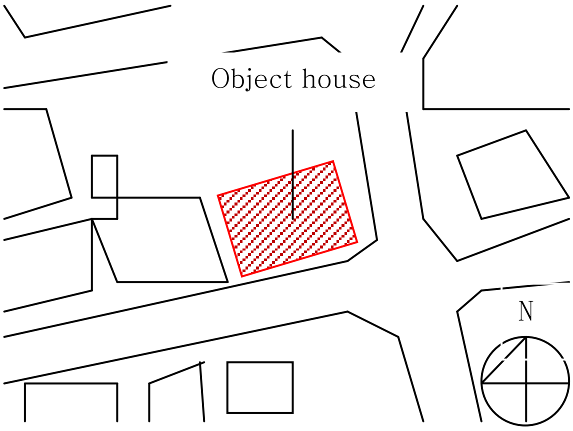

Fig. 2 Surrounding buildings of the house

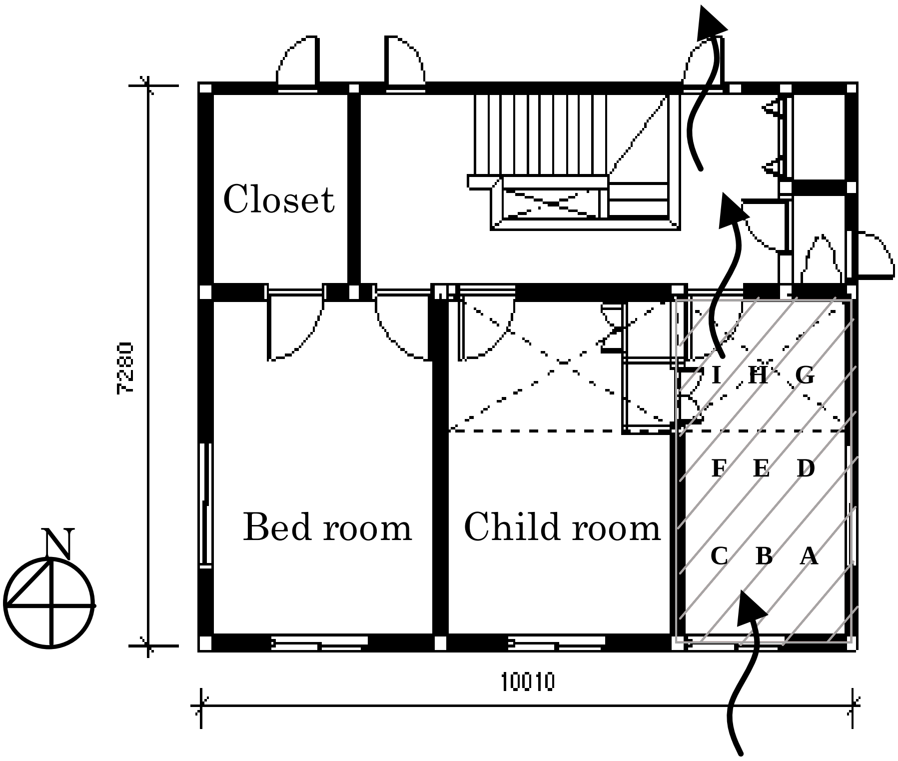

Fig. 3 Plane of the house

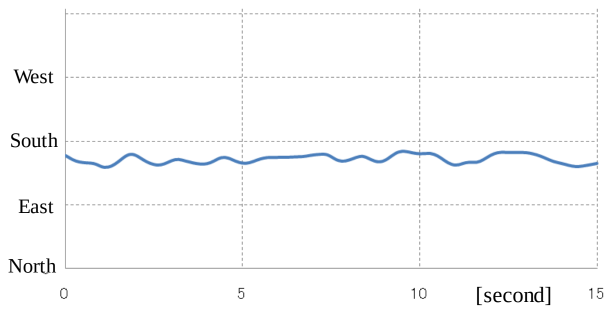

Fig. 4 Outdoor wind direction

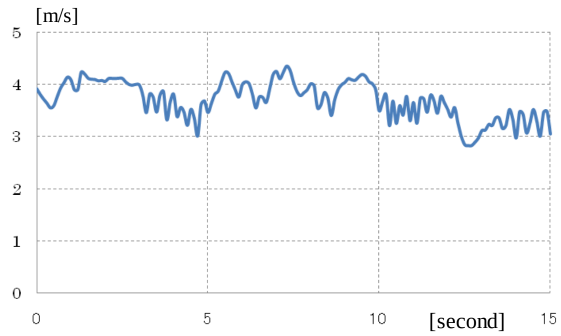

Fig. 5 Outdoor wind velocity

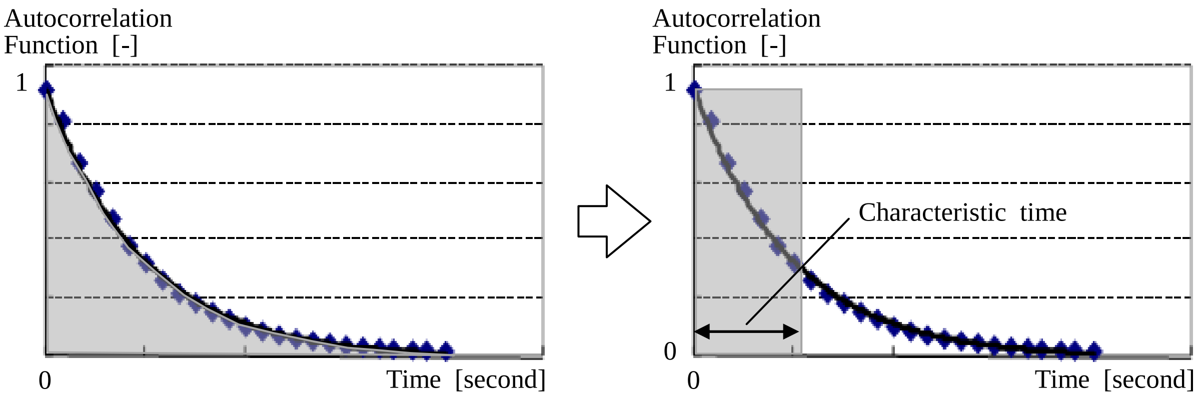

Fig. 6 Basic concept of characteristic time

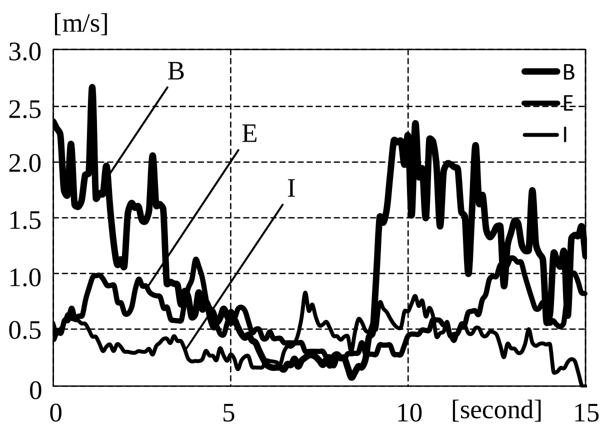

Fig. 7 Synthesized wind velocity in the pathway

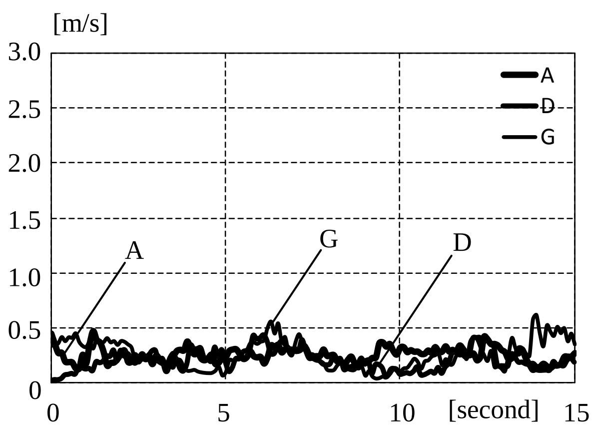

Fig. 8 Synthesized wind velocity out of the pathway

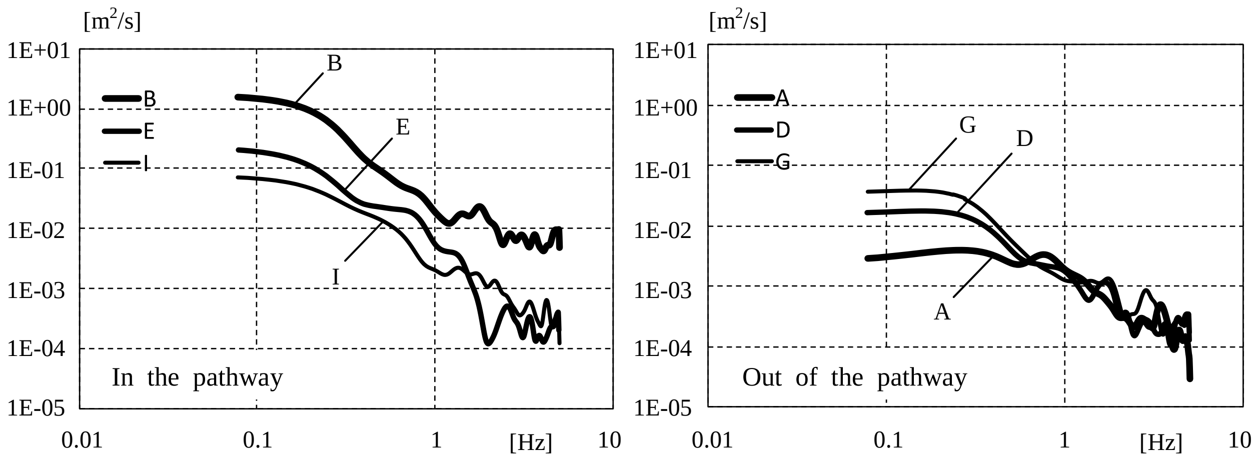

Fig. 9 Power spectrum displayed with respect to each frequency

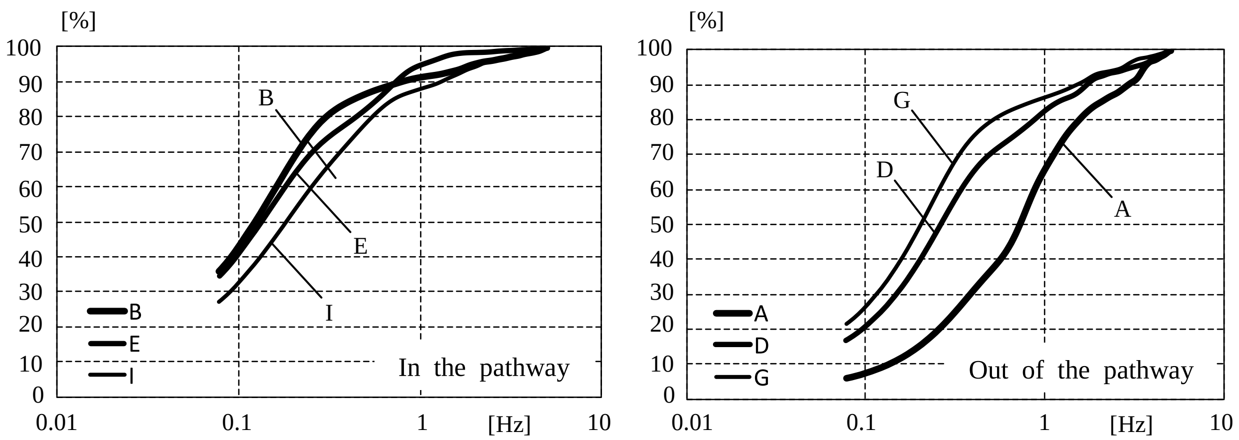

Fig. 10 Cumulative frequency distribution of the power spectrum displayed with respect to each frequency

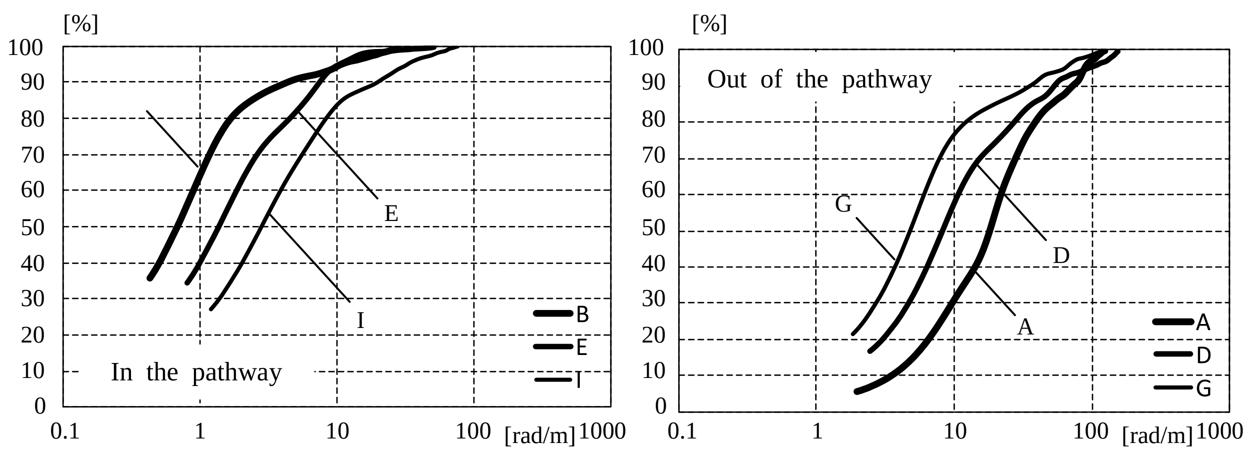

Fig. 11 Cumulative frequency distribution of the power spectrum displayed with respect to each wave number

Table 1 Turbulence statics results

In the pathway	B	E	I
Turbulent velocity [m/s]	0.68	0.25	0.17
Mean wind velocity [m/s]	1.13	0.61	0.41
Characteristic time [s]	1.26	1.30	0.93
Eddy size [m]	0.85	0.32	0.15
Out of the pathway	A	D	G
Turbulent velocity [m/s]	0.07	0.10	0.13
Mean wind velocity [m/s]	0.25	0.20	0.26
Characteristic time [s]	0.24	0.58	0.72
Eddy size [m]	0.02	0.06	0.09