Measurement of Flow Characteristics of a Ceiling Fan with Varying Rotational Speed

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SUMMARY

This paper conducts an experimental measuring of the airflow generated by a modern ceiling fan that has an electronic device to vary the instant rotation speed for simulating natural winds. The measuring results are then used to calculate the mean air velocity, standard deviations, turbulence intensity, equivalent frequency, power spectrum, and other comfort evaluation parameters. The results have shown that, by adopting the natural wind mode, even at a lower mean air velocity, a substantial comfort level can be achieved while consumes much less electric energy. In the consideration of achieving a sustainable built environment, this finding is of great importance. This study also completes a so-called *1/f* power spectrum analysis to identify the feature of natural wind generated. It seems that we can achieve environmental sustainability by further exploring the characteristics of natural environment.

INTRODUCTION

Ceiling fans are widespread used in hot or tropical climate zones for providing cooling and comfort. It consumes relatively low amount of energy in comparison to air-conditioning units. Although in these days, air-conditioning is preferable to operating a ceiling fan in modern office or residential buildings. Complementarily using ceiling fans as additional air circulating devices in air-conditioned rooms can often lead to the same comfort level at an elevated temperature setting, which means a potential saving of energy. Whereas, as ceiling fans are such common appliances nowadays, little effort has been paid on the new fan designs and its consequent influence on room airflow. This paper conducts an experimental measuring of the airflow produced by a modern ceiling fan which has an electronic device to vary the instant rotation speed to simulate natural winds.

The interest of this paper is to investigate the draught caused by a rotating ceiling fan because the space leans to have higher mean velocity. Therefore, thermal comfort considering only mean velocity and temperature as was done in a central air-conditioning system is not enough without considering draught. Draught is defined as an unwanted feeling due to locally convective cooling of the human body caused by air movement. In fact, the sensation of draught has direct relation to the airflow fluctuation, for examples, turbulence intensity and frequency of fluctuation. Several studies relevant to draught and airflow have been performed by Fanger and Christensen [1] and Fanger et al. [2]. In these studies, the percentage of people dissatisfied due to draught was defined by the following equation:

$$DR = (3.14 + 0.37\bar{v}Tu)(34 - t)(\bar{v} - 0.05)^{0.62}, \qquad (1)$$

where *DR* is the percentage of people dissatisfied, $\overline{v}$ mean velocity, *t* air temperature and *Tu* turbulence intensity. Recent study [3] shows that the frequency of air velocity has great impact on draught feeling. In that article, an equivalent frequency parameter was defined to describe the frequency characteristics of the airflow. It indicates that most people are sensitive to airflow at an equivalent frequency between 0.2 and 0.6 Hz. For spaces using a central air conditioning system, the air speed is relatively uniform. Draught can be easily inhibited in such a well-designed system. However, it is not a similar case for the space, using a unitary air conditioner, where persisting air speed might exist in occupied zone. Shih et al. [4] studied the draught induced by a split-type air-conditioner. Their results show that, for such a type of air conditioners, the equivalent frequency falls between 0.3Hz and 0.6Hz, which is in the uncomfortable range.

Recent research in personalized air conditioning systems with fluctuating air movement [5] and simulated natural wind [6] brought out a concept which is different from that of common systems with steady-state air distribution. The fluctuation of airflow is one main factor that affects indoor comfort. According to the research results [7, 8, 9], the fluctuating airflow brings more cooling effect to the human bodies, especially the airflow with a frequency similar to that of natural wind. The research result of [6] shows that the distribution of a constant airflow at the outlet of an air moving devise is quite different from that of a simulated natural wind. Only the airflow reaches its full stage of diffusion ($v < 0.25$m/s), does the structure of the airflow approach to that of natural wind. Nevertheless, the velocity of the air current is too low and has little effect to the thermal comfort.

Power spectrum analysis is an essential tool to be used to analyze the patterns of the airflow. It evaluates the relationship between the frequency of occurrence of the velocity and corresponding magnitude (or the energy) of the air current. The criterion to be used to make the judgment is the slope of the spectrum curve (normally in natural log of base 10). The mathematical relationship of power spectrum density to the slope of spectrum curve can be expressed as $E(f) = 1/f$, where f is the frequency of occurrence of the velocity. According to the finding of relevant literatures, the power spectrum distribution of natural wind is in $1/f$ fluctuation and its slope falls in the range of -1.10 to -1.67. As to the airflow produced by the mechanical devises, its slope of power spectrum curve is approach to the range of $1/f^0$ fluctuation (namely, the range of white noise).

A transient thermal environment can be established by changing the air temperature and/or the air velocity. Simulated natural air movement can be used to offset high air temperature and to improve perceived air quality slightly. A new conditioning strategy focuses on the effective use of simulated natural wind, which has special characteristics in turbulence intensity, velocity distribution and power spectrum. A prediction of energy use shows that substantial energy saving can be achieved by effective use of transient air movement.

In this paper, we focus our experiment upon the flow phenomena of a ceiling fan since such an air devise is believed to be able to achieve a certain degree of thermal comfort with energy saving. The results of the experiment are then studied and evaluated respectively for mean air velocity, velocity distribution, turbulence intensity, equivalent frequency and power spectrum etc., of the airflow produced. The corresponding indices reflect some well-known approaches for evaluating the comfort and thermal pleasance in a warmer environment and for preventing cold draught, in particular, in an air-conditioned space.

METHODS

The ceiling fan to be studied was installed in an open space indoor, as shown in Figure 1, providing airflow blowing down to the space below it. A hot wire anemometer made by TSI Co., Model IFA300, displayed in Figure 1(b) was used to measure the airflow characteristics. The instrument has the maximum scanning rate up to 1MHz. But, in this study, the scanning rate of the anemometer was set to be 10Hz. which can best demonstrate the *1/f* features and avoid unwanted noises. So the data of air speed was recorded once every 0.1 seconds. The measuring time lasted approximately for 6.8 minutes and 4096 data sets were recorded for every single measuring point. Longer data logging time was also tried, but the deviations of results analysis are less than 5%.

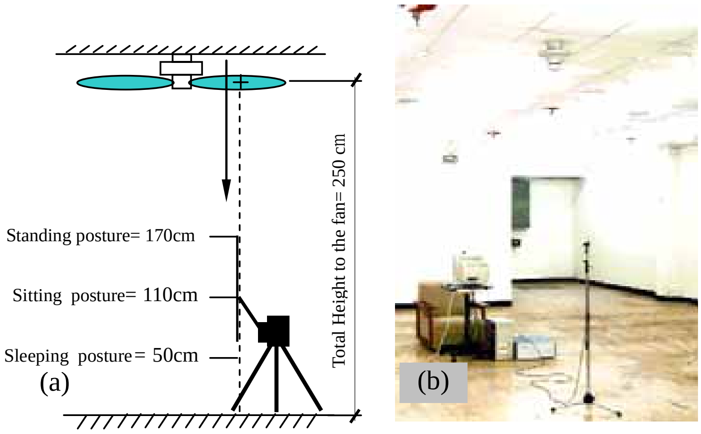


Figure 1. Layout of test site and some representative measurement heights

The speed of the air delivered is measured in a matrix consisted of several measuring points below the fan, as shown in Figure 2. A preliminary study for the fan speed is initiated where a series of measuring points are taken horizontally, 100 cm below the fan. Experimental setup shows that the ceiling fan is equipped with the fan blades in a spindle shape. The air distribution of the fan exhibits a unique pattern that the higher speed occurs somewhere below the center of the fan blade and the velocity declines as the measuring points are gradually away from the center, as Figure 2 shows. The measuring results are then used to calculate the mean air velocity, standard deviations, turbulence intensity, equivalent frequency, power spectrum, and other flow characteristic parameters.

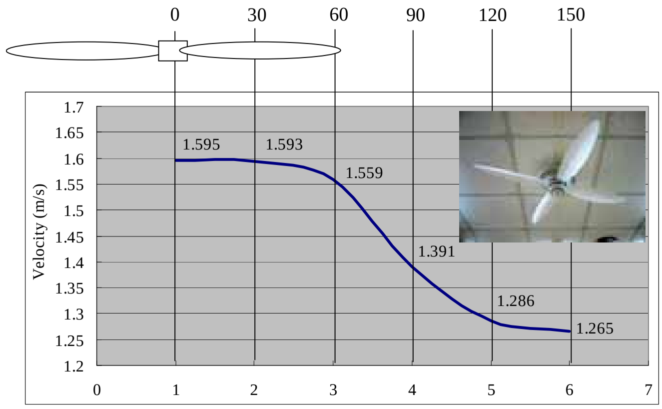


Figure 2. Profile of mean air velocity generated by the studied ceiling fan at height 150cm (fan was set at medium rotation speed)

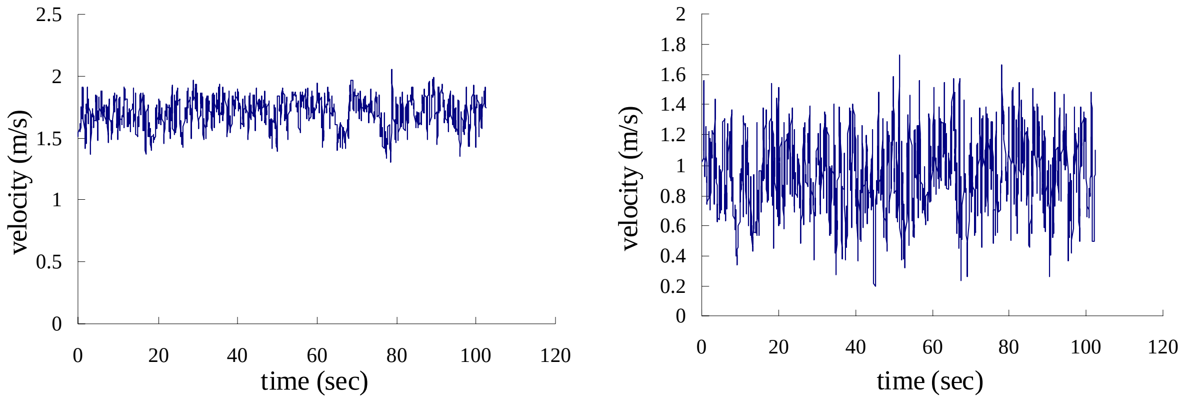
RESULTS

The ceiling fan studied in this paper, unlike the traditional one only operating at a constant rotation speed, can make fan blade subject to an instant speed change, with the aim to simulate nature breeze. It is claimed that the additional variable speed function can make occupants feel more comfortable in this indoor environment.

In order to find out the difference of air velocity variations for the ceiling fan operating at the constant speed mode and the variable speed mode, a measuring point located at the half of the blade length and 100 cm down from the fan blades was chosen to represent the flow characteristics in the occupied zone subject to direct air moving. The measuring results are shown in Figure 3-5 (a), correspondent to fan rotation in high, medium and low speeds. Basically, in the constant rotation speed mode, air flow measured at this location shows that the mean air velocities are around 1.4~1.7m/s, and the fluctuations are in the scopes of 0.2~0.3m/s.

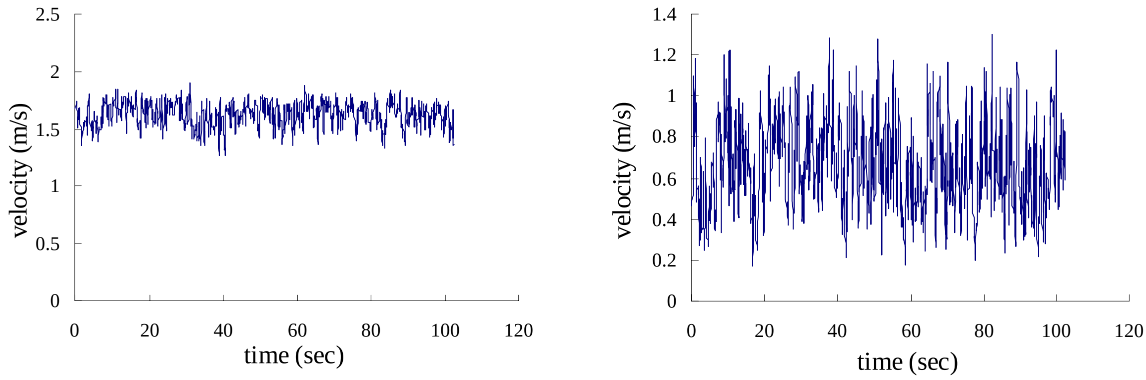
In contrast, when the fan was operating in the variable speed mode, the air velocities measured, as shown in Figure 3-5(b) for different fan speed settings, all demonstrate the instantaneous velocity varying with time and show erratic change in fluctuation scale significantly larger than that of the constant speed cases. If we observe Figure 5(b) in more detail, the change of air velocity for the low-speed fan rotation condition was found with a specific fluctuation pattern. In some cases, the air speed measured even dropped to a very low speed to the extent about 0.2m/s, the condition lasting for about 20 seconds, and then the fan was quickly increased speed again. However, after observing the air velocity change for a longer time, it was found that the air speed pattern was not very repeated and the fan speed modulation could be explained as a random act.

The air speed variation shown in Figure 3-5, by using some statistical analysis techniques, the data in time-domain can be converted to some flow characteristics in frequency-domain, and the results are shown in Table 1. Obviously, when the fan operating in natural wind mode, the mean air velocities are comparatively lower than those of constant speed mode, but the standard deviations of velocity and acceleration are roughly 2~3 times higher. The combined effect of a lower mean air velocity and a larger flow fluctuations results in a much stronger turbulence intensity for the natural wind cases. As indicated in Equation (1), turbulence intensity is the main cause, beside the temperature and speed differences, to introduce cold draught which has a direct impact on occupant's feelings of comfort. In order to calculate the percentage of people dissatisfied with the draught. An average indoor temperature of 28^{o}C was chosen for the places using the tested ceiling fan in which the room temperature can be kept at a higher level than the normal setting in a traditional air-conditioned environment. The calculation results are shown in Table 1 in term of parameter *DR*. Surprisedly, though with higher turbulence intensity, the natural wind cases present lower *DR* values, mainly because of smaller mean air velocities. Hence, based on these results, fan operating in the natural wind mode can be inferred to achieve higher comfort levels and energy conservation.



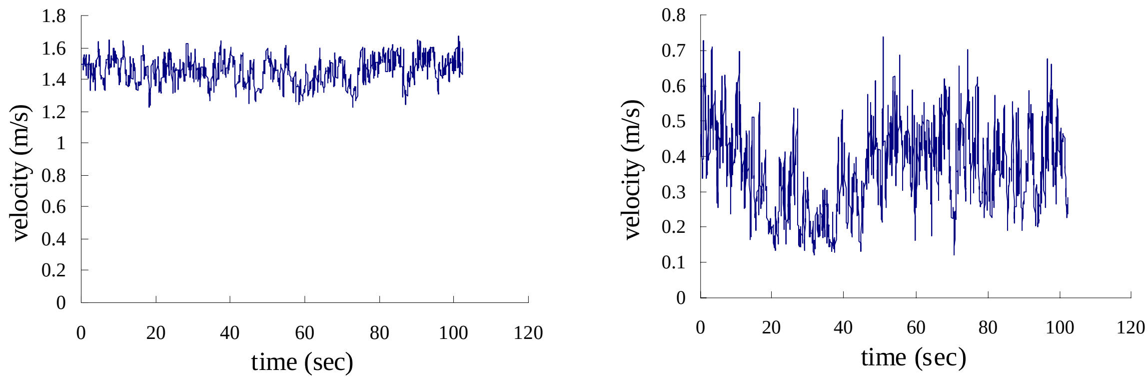
(a) constant speed mode (b) natural wind mode

Figure 3. Velocity fluctuations for ceiling fan rotating at the high-speed setting



(a) constant speed mode (b) natural wind mod

Figure 4. Velocity fluctuations for ceiling fan rotating at the medium-speed setting



(a) constant speed mode (b) natural wind mode

Figure 5. Velocity fluctuations for ceiling fan rotating at the low-speed setting

To further explore the flow characteristics of the main air flow and the induced air motion, six data points were selected to calculate the parameters, as listed in Table 2, to stand for the features in two different flow regions. As the velocity profile shown in Figure 2, measuring points, PT-8,20,32 were positioned at half of the fan blades and 60,120,180 cm under the fan rotation plane. These positions can be interpreted as the heights of the fan discharge, standing and sitting postures of occupant, respectively, in which are under the influence of direct fan blowing. The other three measuring points, PT-10,22,34, were measured at the similar heights of the former group but are about 30 cm away from the tip of fan blade. In this region, the air motion is mainly induced by the main air stream such that the mean velocities are relatively small. Interesting phenomena can be found in Table 2 that, in the natural wind mode, the mean air velocity differences between these two regions are clearly larger than those in the constant speed mode. When the probe was being moved outside of the coverage of the rotating fan blades, the measured wind velocities rapidly decreased to about 0.2m/s, a speed often encountered in a central air conditioning system. In addition, the issue of discomfort caused by draught (*i.e. DR*) becomes almost negligible.

Table 1. Statistical analysis on the flow characteristics of a ceiling fan which operates in constant speed mode and natural wind mode respectively (at room temperature 28 ^oC)

(a) constant speed mode			
Statistics parameters	high-speed	medium-speed	low-speed
MEAN	1.7041	1.6242	1.4537
SD-v	0.1253	0.1058	0.0834
SD-a	1.1020	0.9108	0.6068
Tu	0.0735	0.0651	0.0573
DR	26.1185	25.2718	23.4763
fe	1.4003	1.3705	1.1586
1/f	1.00	0.98	1.20
(b) natural wind mode			
Statistics parameters	high-speed	medium-speed	low-speed
MEAN	0.9400	0.6658	0.3236
SD-v	0.2602	0.2167	0.1217
SD-a	2.7014	1.9572	0.7999
Tu	0.2767	0.3255	0.3761
DR	18.0645	14.3047	8.5555
fe	1.6527	1.4374	1.0462
1/f	0.63	0.83	1.10

The frequency of flow fluctuations will also affect occupant's perception of comfort. To identify the influence from the frequency aspects, two common statistical analysis methods are used: the first one is the so-called equivalent frequency. It is a function of the instant changes of wind velocity and the corresponding acceleration. According to the quoted literatures, equivalent frequency in the range of 0.2-0.6 Hz, the human body is most likely to suffer from the cold draught. The second one is the so-called *1/f* fluctuation index, which is the slope of linear equations in a logarithm plot of speed vs. frequency obtained from the Fourier transformation of air velocity. Based on the literatures, when this factor is less than 1.0, it represents that the air stream is still in the process of developing; when larger than 1.0, the air movement is caused by induction; when closer to 1.0, the air flow characteristics is more similar to a natural wind spectrum, and the human comfort level will be increased. Table 2 shows the calculation results for the ceiling fan rotating in a constant speed and in variable speed modes. The equivalent frequency (*fe*) are not in the aforementioned frequency range which is most likely to cause uncomfortable draught. In the aspect of *1/f* analysis, the results for most cases are all close to 1.0. The ceiling fan might demonstrate a more uniform air flow in comparison to a conventional jet-flow-typed air distribution device due to the slow rotation speed and large fan blade of a ceiling fan. No matters operating in the constant speed or the natural wind mode, the measured air velocity, after making Fourier transform, are found contribute insignificant differences on the slopes of *1/f* curves for different conditions. It is indeed a surprising finding.

Table 2. Statistical analysis on the flow characteristics at two lines of measuring points representing the circumstances of direct wind blast and induced air motion respectively (at room temperature 28 ^oC)

(a) constant speed mode						
Statistics	PT-8	PT-20	PT-32	PT-10	PT-22	PT-34
MEAN	1.7433	1.5999	1.5447	1.3326	1.4006	1.4034
SD-v	0.1244	0.1301	0.1392	0.0466	0.1018	0.1094
SD-a	1.1898	1.1072	0.9606	0.2212	0.6257	0.5668
Tu	0.0713	0.0813	0.0901	0.0350	0.0727	0.0780
DR	26.4982	25.1001	24.5681	22.1046	22.9712	23.0211
fe	1.5224	1.3543	1.0983	0.7548	0.9781	0.8244
1/f	0.8000	0.9100	1.0000	1.3000	1.2000	1.2000
(b) natural wind mode						
Statistics	PT-8	PT-20	PT-32	PT-10	PT-22	PT-34
MEAN	0.7649	0.6641	0.5053	0.2279	0.1932	0.2466
SD-v	0.3452	0.3123	0.2477	0.0828	0.0692	0.1193
SD-a	2.3599	2.2190	1.5464	0.5040	0.3096	0.5919
Tu	0.4514	0.4703	0.4903	0.3634	0.3583	0.4836
DR	15.9227	14.4370	11.9047	6.5218	5.6929	6.9689
fe	1.0879	1.1307	0.9934	0.9686	0.7117	0.7900
1/f	0.9200	0.8800	0.9500	1.2000	1.3000	1.2000

DISCUSSION

In this paper, the measurement of a new ceiling fan, which can vary its instant motor rotation speed to simulate a natural wind pattern, has shown that by adopting the natural wind mode operation, even at a lower mean air velocity, a substantial increase of airflow turbulence intensity can be easily achieved. Hence it, in terms, results in a better comfort level while consumes much less electric energy. In the consideration of achieving a sustainable built environment, this finding is of great importance. But according to the literatures, the so-called natural wind must present itself as a linear equation with the negative slope close to a value of 1.0 in a logarithm plot of velocity vs. frequency. It is surprised that the characteristic values have no significant difference no matter the ceiling fan is operating in a constant speed or natural wind mode. The results might indicate that the judgment of comfort should utilize multiple analysis methods, rather than a single target analysis method. A coherent argument about the description of comfort for the present study seems not fully established yet. However, it is believed that through continuous in-depth studies, we can achieve environmental sustainability by further understanding the characteristics of natural environment.

ACKNOWLEDGEMENT

This project is made possible by the financial support from the Bureau of Energy, the Ministry of Economic Affairs, Taiwan, ROC.

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