Comfortableness of Fluctuating Air Flow

—Subjective Assessment of the Air Flow of an Air-conditioner with 1/f Fluctuating Fan Speed—

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Abstract : Fluctuations in which spectral density are inversely proportional to frequency are called 1/f fluctuations. This type of fluctuation has been found in a variety of phenomena. The 1/f fluctuations are presumed to be comfortable because music and other comfortable phenomena have this type of fluctuation. The purpose of this study is to examine the comfortableness of the fluctuating air flow of an air-conditioner which fan speed was controlled by the 1/f fluctuation. 157 subjects (75 males and 82 females) participated in this experiment and half of them wore ear plugs to investigate the effect of the fan noise. Two types of fluctuating air flow of an air-conditioner (wide range fluctuation and narrow range fluctuation) and laminar air flow were evaluated by the rank order test, the open-ended method and the semantic differential method. Our results indicated that wide range fluctuating air flow was most uncomfortable because of its fluctuating fan noise. The comfortableness of the narrow range fluctuating air flow and the constant one are almost equal. Moreover, factors which affect the subjective comfortableness are discussed.

Key words : 1/f fluctuation, air flow of an air-conditioner, comfortableness, semantic differential method.

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Introduction

Fluctuations in which spectral power density is inversely proportional to frequency are called “1/f (one-over-f) fluctuations” or “1/f noise”. The 1/f fluctuation has been found in a host of physical and biological systems such as semiconductors (Boehm *et al.*, 1977), wood patterns (Musha, 1980), alpha wave of the EEG (Suzuki *et al.*, 1980), heart beat (Kobayashi & Musha, 1982; Saul *et al.*, 1988), neural axons (Musha *et al.*, 1981), human tapping intervals (Musha *et al.*, 1985), and so on. On the other hand, Voss (1975, 1977) analyzed the fluctuations in the loudness of many musical selections and found that spectral densities were 1/f-like. Thus, the facts that 1/f fluctuation can be found in human biological phenomena and that 1/f-modulated electric stimulation is more effective for pain suppression than periodic electric stimulation (Suzuki *et al.*, 1980) suggest that 1/f fluctuation is beneficial to both our human body and its sensations. Furthermore, some comfortable natural sounds, for example, murmuring of a stream or sound of the sea have 1/f loudness fluctuation (Musha, 1977). Even though 1/f fluctuation may be comfortable for us, there are

few systematic studies on the effects of $1/f$ fluctuation on man.

The purpose of this study was to examine by means of the subjective estimation method whether the air flow of the air-conditioner, which fan is fluctuated by the $1/f$ fluctuation, is more comfortable than a laminar air flow.

Methods

A few algorithms are available to generate the $1/f$ fluctuation (see Appendix); 1) Mandelbrot-Weirestrass function (Berry & Lewis, 1980; Teramoto *et al.*, 1985), 2) The 0.5th order integration of white noise (non-integer integration and differentiation are defined by the Fourier transformation. Takayasu, 1986), 3) Superimposition of sinusoids which amplitudes are proportional to $1/f$.

Easier methods to obtain $1/f$ fluctuation are the extraction of $1/f$ fluctuation from music (Kosugi *et al.*, 1978) or other phenomena which include $1/f$ fluctuation. Furthermore, $1/f$ fluctuation can be also generated by simulating the tossing of 10 dice (Gardner, 1978). The 3rd algorithm is devised by the authors and used in this study to obtain $1/f$ fluctuation (Fig. 1).

Fig. 1. Synthesized $1/f$ fluctuation and its power spectral density.

Fig. 2. A wave form of the wide range fluctuation for air-conditioner fan speed control.

This synthesized pattern was modulated to two types of fluctuations: wide range fluctuation (W: range = 400 rpm) and narrow range fluctuation (N: range = 200 rpm). Each fluctuation pattern was converted into discrete values with 20 rpm step (Fig. 2). The fan speed of the air-conditioners was controlled by a computer program which included these 1/f fluctuation patterns. The average fan speed was 1400 rpm and was approximately equal to the fan speed of the "M" position (medium) of the wind intensity controller of the air-conditioner. In order to evaluate the effects of the fluctuation and to exclude the contribution of the temperature of the air flow, the compressors of the air-conditioners were not used. Therefore, the temperature of the test room was controlled by the set-in air-conditioner system and held roughly constant (25 centigrade/77 Fahrenheit). The two types of fluctuating air flow mentioned above and the laminar air flow (C) were compared. Each subject was exposed to the three kinds of air flow at random for 150 seconds with 30 seconds intervals.

Two experimental sessions were performed in this study. Fifty-two female subjects (age: 19–24 yrs.) participated in the first session. Twenty-seven of them (silent group) wore ear plugs (North Decidump) and the others wore no hearing protectors (normal group). Groups of six subjects were prepared for the experiment at the same time. First, they entered the preparatory room in which the room temperature was controlled to be approximately the same as that of the test room and rested for around 5 minutes to adjust themselves to the experimental conditions. During this resting period, subjects were instructed to compare three kinds of air flow and rank their comfortableness (rank order test). They were also asked to write down their feelings in regard to the air flow, for instance, 'liked the

breeze' or 'felt uncomfortable' and so on (this method is called the open-ended method). They then entered the test room (6.3 m×5.3 m) and seated themselves in the chairs. Three air-conditioners were put on iron racks, separated 1 m from each other. The height of the fan was 1.2 m from the floor and the distance from subjects was 2 m. In this way, the subjects were exposed to a mainly horizontal air flow from the front. The first session was performed on 1st, 12th and 13th of July.

In the second session, one hundred-five subjects (75 males and 30 females) were divided into two age-matched groups, i.e. silent group and normal group. Thirty-seven male subjects (age: 24–55 yrs., mean age 32.8 yrs.) wore ear plugs and thirty-eight male subjects (age: 24–57 yrs., mean age 33.3 yrs.) wore no ear plugs. Half of the female subjects (age: 19–40 yrs., mean age 25.4 yrs.) wore ear plugs and the other female subjects (age: 19–46 yrs., mean age 25.4 yrs.) wore no ear plugs. The second session was performed on 30th and 31st of August.

The rank order test, the open-ended method and the semantic differential (SD) method were performed. Twelve pairs of adjectives selected from the expressions of the open-

No. _____

name

【1st】

fairly	slightly	slightly	fairly
cold	-----		warm
refreshing	-----		gloomy
light	-----		heavy
soft	-----		hard
dry	-----		wet
comfortable	-----		uncomfortable
natural	-----		artificial
strong	-----		weak
feel good	-----		feel bad
variable	-----		monotonous
snug	-----		uneasy
familiar	-----		unfamiliar
restful	-----		restless
fine	-----		inconstant
healthy	-----		unhealthy
calm	-----		excitable
mountain/highland	-----		sea/seashore
spring wind	-----		autumn wind

Fig. 3. Form of the semantic differential (SD) method.

ended method in the first session and six pairs of adjectives which are usually used in the SD method were contained in the SD questionnaire (Fig. 3). Subjects were instructed to circle the horizontal bars in each adjective scale according to their feelings to the stimuli. The factor analysis and the method of successive categories were performed to analyze the results of the SD method.

The rankings were converted to average rankings and the multiple comparison (Ryan procedure) was performed for the statistical significance test.

Results

The average rankings of each group are shown in Fig. 4. Results of the female subject group are shown as pooled data of session I and II. In the male-normal group and female-normal group, it is shown that the narrow range fluctuation was more comfortable than the wide range fluctuation ($P < 0.05$, $P < 0.05$). No significant differences were found among stimuli in other groups.

The expressions described in the open-ended method were classified into six categories (Table 1). Three of them were comfortable (positive) images and the others were uncom-

Fig. 4. Averages of rank order test (Mean $\pm$ SE). Significant level; * $P < 0.05$.

Table 1. Categorical classification of results of the open-ended method

Image	Expression
POSITIVE	
A: comfortable	comfortable, natural, refreshing, breeze, autumn wind, spring wind
B: water side	wave, seashore, beach, lake, sea
C: green	highland, field, mountain, forest, tree shade
NEGATIVE	
D: uncomfortable	uncomfortable, unnatural, languor, heavy, harsh, annoying
E: stimulating	storm, typhoon, winter
F: artificial or monotonous	artificial, air-conditioner, electric fan, monotonous, unsatisfactory, weak

fortable (negative) images. These classified expressions of session I and II were pooled and the chi square test was performed (Table 2). The number of expressions related to uncomfortableness (image: D) to the wide range fluctuation was more than to other stimuli. The number of expressions related to the image category "F" (artificial or monotonous) to the constant air flow was more than the others. Significant differences were found in all

Table 2. Results of the open-ended method in all subjects (157). Figures in the table are number of subjects who expressed the images listed in the left column

Image	W	N	C	χ^2
A	31	45	35	2.81
B	14	10	5	4.21
C	6	11	3	4.90
D	39	16	6	28.16**
E	15	8	2	10.16**
F	7	9	36	28.71**

** $P < 0.01$

Image A–F : see Table 1

W : wide range fluctuating air flow, N : narrow range fluctuating air flow,

C : constant air flow

Fig. 5. Mean rating values normalized by the method of successive categories (Mean $\pm$ SE). Significant level; * $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$.

□ wide range fluctuating air flow
 ▨ narrow range fluctuating air flow
 ▤ constant air flow

three images related to uncomfortableness ($P < 0.01$).

The factor analysis of the SD method extracted three major factors, the factor of evaluation, the factor of potency and the factor of activity (Iwashita, 1983). Three adjective pairs, “refreshing-gloomy”, “comfortable-uncomfortable” and “snug-uneasy” are related to the evaluation factor. The scales “strong-weak” and “calm-excitable” are related to the potency factor and the scales “variable-monotonous” and “fine-inconstant” are the active factor.

Subjective rating values of the three scales of the evaluative factor were transformed to fit the normal distribution by the method of successive categories. After the transformation, mean values were obtained. Figure 5 shows the mean rating values to each stimulus. In the male-normal group, refreshingness of the narrow range fluctuating air flow was significantly higher than the wide range fluctuating air flow ($P < 0.01$). In the female-silent group, both the narrow range fluctuating air flow and the constant air flow were more refreshing than the wide range fluctuating air flow ($P < 0.05$, $P < 0.01$, respectively). The constant air flow was evaluated “more refreshing” in the male-silent group than in the male-normal group ($P < 0.05$). The wide range fluctuating air flow was evaluated “more

Fig. 6. Three dimensions of semantic space. See text.

▲ wide range fluctuating air flow (▼ negative value)

■ narrow range fluctuating air flow

● constant air flow

solid line: male-silent, short broken line: male-normal, long broken line: female-silent, chain line: female-normal

comfortable" in all adjective scales (refreshing, comfortable and sung) in the male-silent group than in the male-normal group ($P < 0.001$, $P < 0.05$, $P < 0.05$).

Furthermore, rating values are pooled in each factor and average rating scores were obtained. Figure 6 shows average rating scores to each stimulus in every subject group plotted in the 3 dimension of semantic space. Length of bars represent the mean evaluative factor score (i.e. comfortableness). It is shown that all data were nearly along the activity axis and that length of bars of filled circles (C) and squares (N) are longer than those of triangles (W). This figure represents clearly the difference between images to each stimulus in each subject.

Discussion

In this study, subjects were exposed to three kinds of air flow for 150 seconds with 30 seconds intervals and were asked to compare stimuli with each other. In this manner, subjects finished their subjective evaluations to the three kinds of the stimuli within ten minutes. The appropriateness of this time schedule was not testified. In order to compare stimuli, it is better that the stimuli are represented at the same time. For instance, visual stimuli are able to be represented simultaneously. However, in case of air flow stimuli, it is impossible to represent simultaneously. Therefore, in order to have subjects judge more easily and to extract their first impressions to stimuli, durations of the representation and intervals were made relatively short. Furthermore, the order of the representation was randomized.

The $1/f$ fluctuating air flow is able to be observed at the point close to the fan which speed is fluctuated by the $1/f$ fluctuation (personal communication). However, high frequency components of the air flow fluctuation at the far point from the fan will decrease due to the inertia of the air. Therefore, the slope of the spectrum of the air flow fluctuation at the far point becomes steep ($1/f \rightarrow 1/f^2$). In the present study, the distance between subjects and the air-conditioner fan was 2 m and it seems that subjects were not too far from the fan. Probably the air flow fluctuation at the subjects' position was not exactly $1/f$ fluctuation, but '1/f-like'.

In the male-silent group, there was no significant difference between stimuli, however, in the female-silent group, significant difference was found in the 'refreshing' scale among the wide range fluctuating air flow and both the narrow range fluctuating and constant air flow as shown in Fig. 5. Though, it seems that this result suggests that the sensitivity to the air flow is different between man and woman, as almost all of the female subjects wore skirts the extent of exposure of skin surface was different between male subjects and female subjects. Therefore, it is impossible to determine whether the difference of results between female subjects and male subjects was due to the sex difference or the difference of clothes.

The statistical results indicate that the narrow range fluctuating air flow was a little more comfortable than the laminar one, and that the wide range fluctuating air flow was

most uncomfortable. However, some subjects felt comfortable during the wide range fluctuating air flow and they described their feelings to this air flow as a natural breeze in the open-ended method. Moreover, some other subjects felt uncomfortable during narrow range fluctuating air flow or constant air flow. Thus, subjective responses to the same stimulus are different among individuals.

Uncomfortableness to the wide range fluctuation is probably caused by aversion to the varying (fluctuating) fan noise rather than the fluctuating air flow itself because the wide range fluctuating air flow was evaluated as more uncomfortable in the male group without ear plugs than in the male group with ear plugs. Probably, some subjects who felt uncomfortableness to both the narrow and wide range fluctuating air flow may believe that the air flow of an air-conditioner is mechanically constant. Therefore, it seems that they felt uncomfortable or unnatural to the fluctuation of the fan noise and the air flow because they complained of disgustfulness (i.e. the air conditioner changes its air velocity automatically as if it has a will of its own).

In this study, we attempted to mimic a natural breeze by 1/f fluctuating air flow. Namely our hypotheses were; 1) natural breeze is comfortable, 2) natural breeze may have 1/f fluctuation, 3) comfortable phenomena such as music has 1/f fluctuation and 4) 1/f fluctuation can be found in human biological phenomena, therefore, 5) 1/f fluctuating air flow of an air-conditioner would be more comfortable than laminar air flow of an air-conditioner. However, it is questionable whether comfortableness from a natural breeze is caused by its fluctuation. The natural environment in which a person feels a breeze may also contribute to one's comfortableness. That is, even if we take out only one physical characteristic, for example 1/f fluctuation, from the natural breeze and apply it to the wind of an air-conditioner, it is presumed that people will not feel comfortable unless they realize that they are being exposed to this characteristic of a natural breeze.

When subjects are exposed to low noise level [45 dB (A)] white noise (frequency characteristics of this noise are similar to that of the sound of a waterfalls) with a picture of a falls projected on the screen in front of them, their subjective assessments of annoyance to the noise are relatively lower than those without a picture (Tanaka *et al.*, 1981). Thus, if the intensity of the stimuli is not too strong, it seems that subjective evaluation to the stimuli depends on a cognitive factor, i.e. subjects' recognition or association of what the stimulus is, rather than its physical characteristics.

Further investigations in which the air flow fluctuation is measured and the comfortableness of the air flow is evaluated objectively, for instance by means of some physiological indices, should be done.

Conclusion

1. The comfortableness of the narrow range fluctuating air flow was almost the same as that of the constant air flow.

2. The wide range fluctuation was evaluated as uncomfortable. It is suggested that this uncomfortable feeling is caused by a fluctuating noise.

Appendix

- 1) Mandelbrot-Weirestrass function

$$W_D(x) = \sum_{n=-\infty}^{\infty} \frac{1 - \cos(Y^n \pi x)}{Y^{(2-D)n}} \quad : D=1.99, Y=1.5$$

- 2) Non-integer differentiation

$$\frac{d^n}{dx^n} f(x) = \frac{1}{2\pi} \int_{-\infty}^{\infty} (-ik)^n g(k) \cdot e^{ikx} dk$$

$$g(k) = \int_{-\infty}^{\infty} f(x) \cdot e^{-ikx} dx$$

- 3) Superimposition of sinusoids

$$X_i = \sum_{j=1}^{40} A_{ij} \sin(2\pi f_{ij} + \theta_j) \quad : i=1, n \ (n=1024)$$

$$A_{ij} = 10 \times f_{ij}^{-1/10}$$

$$f_{ij} = 0.5 \times 10^{j/20} (1 + f_0 \times i/n) \quad : f_0 = 10^{1/20} - 1$$

$$0 \leq \theta_j \leq 2\pi \quad [random]$$

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ゆらぎ風の快適性

—1/f ゆらぎのファン回転を持つエアコンの気流の主観的評価—

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要 旨: 1/f ゆらぎとはスペクトルが周波数 f に反比例するようなゆらぎの総称である。このようなゆらぎは、自然界に多く観察され、脳波などの我々の生体現象や、音楽、小川のせせらぎなどの快い事象も 1/f ゆらぎに近いことから、1/f ゆらぎは我々にとって快いものであろうことが推測される。本研究では、エアコンのファン回転数を 1/f でゆらがせたときの吹き出し風の快適性を主観的評価法により評価し、ゆらぎ風の快適性について検討した。被験者は 157 名（男性 75 名、女性 82 名）で、ファン騒音の影響を評価するため、半数の被験者に耳栓を着用させた。ゆらぎの振幅の異なる強ゆらぎ条件と弱ゆらぎ条件の 2 つのゆらぎ風と定常風が、順位法、自由記述法および SD 法 (Semantic Differential Method) により評価された。その結果、強ゆらぎ条件が最も不快であることが示された。これは、気流のゆらぎよりも、むしろファン騒音のゆらぎに起因するものであることが示唆された。一方、弱ゆらぎ条件と定常条件は、ほぼ同じ快適性を示した。さらに、主観的な快適感に影響を及ぼす因子について考察した。

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